GREEN INFRASTRUCTURE AND ITS EFFECT ON AIR QUALITY

METHODOLOGY OF PLANTING GREENERY IN URBAN AREAS IN ORDER TO CAPTURE POLLUTION

EUROPEAN UNION
European Regional Development Fund

978-80-88399-03-2 (paperback)
978-80-88399-04-9 (online: pdf)

European Union
European Regional
Development Fund

UIA URBAN INNOVATIVE ACTIONS

CLAIRO CLEAR AIR AND CLIMATE ADAPTATION IN OSTRAVA AND OTHER CITIES

OSTRAVA!!!

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PUBLISHED BY: STATUTORY CITY OF OSTRAVA / STRATEGIC DEVELOPMENT DEPARTMENT, 2021

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This project is co-financed by the European Regional Development Fund through the Urban Innovative Actions initiative.

LIST OF ABBREVIATIONS

SYMBOLS:

b	empirical constant equal to 14 m^{-1}
c(z)	concentration of a component at height z above the surface
C	outer surface of the crown (m)
b	empirical constant equal to 14 m^{-1}
D	molecular diffusion of gas
DBH	diameter at breast height
D_{H2O}	diffusion coefficient of water
D_i	diffusion coefficient for gas component
d_k	mean crown projection area (m)
F	deposition flux of pollutant (g m^{-2} s^{-1})
F_{sto}	stomatal flux O_3
G	global radiation (W/m^2)
go_3	current stomatal conductance
g_{max}	average maximum stomatal conductance of O_3 of a tree (mmol O_3 m^{-2} s^{-1})
g_{phen}	g_{max} modification during phenological changes
g_{light}	g_{max}modification during light changes (μmol $m^{-2}s^{-1}$)
g_{temp}	g_{max}modification during air temperature changes (°C)
g_{VPD}	g_{max} modification during vapour pressure deficit (kPa)
g_{SWP}	g_{max}modification during soil water potential (Mpa)
g_{min}	minimum stomatal conductance during the daylight period
h	vegetation height (m), crown height (m)
k	von Kármán constant (0.4)
L	Monin-Obukhov length (m)
LA	leaf area
LAI	leaf area index
LAD	leaf are density
PM_x	category of suspended particulate matter, where x=1, 2.5 or 10 is their aerodynamic diameter (μm)
R_a	aerodynamic resistance (s cm^{-1})
R_b	laminar resistance (s cm^{-1})
R_c	surface resistance (s cm^{-1})
R_{ext}	canopy cuticle or external leaf resistance (s cm^{-1})
R_i	input resistance (s cm^{-1})
R_{inc}	incanopy resistance (s cm^{-1}) Rm mesophyll resistance (s cm^{-1})
R_{soil}	soil resistance (s cm^{-1})

R_{sto}	stomatal resistance (s cm^{-1})
S	mean shading coefficient
SAI	surface area index
Q	amount of pollutant captured in vegetation (g)
Sc	Schmidt number
t	time (s)
T_s	surface temperature (°C)
u_*	friction velocity (m s^{-1})
u_z	horizontal wind velocity at height z above zero-plane displacement (m s^{-1})
$v_d(z)$	deposition velocity at height z above surface (cm s^{-1})
V_{st}	particle settling velocity (cm s^{-1})
z	height above surface (m)
z_0	surface roughness (cm)
ψ_m	stability-correction function for momentum
ψ_c	stability-correction function for pollutant concentration
x_s	shading factor
y	amount of resuspended particles PM_{10} (g m^{-2})

ACRONYMS:

APM	Automatic pollution monitoring
CAS	Czech Academy of Sciences
CLAIRO	Clean Air and Climate Adaptation in Ostrava and Other Cities
GIS	Geografic Information System
GPS	Global Positioning System
ISKO	Air Quality Information System
VOC	Volatile organic compounds
VSB	VSB-Technical University of Ostrava

NAMES:

CHMI	Czech Hydrometeorological Institute
CR	Czech Republic
EU	European Union
NIPH	National Institute of Public Health
US EPA	United States Environmental Protection Agency
WHO	World Health Organization
HI	Health Institute

CONTENTS

I. INTRODUCTION

The aim of this article is to describe the methods and results that have been obtained so far in the CLAIRO (Clean Air and Climate Adaptation in Ostrava and Other cities) project. The main goal of the CLAIRO project is to design the structure and composition of green infrastructure with the maximum capacity to capture air pollutants (ozone, nitrogen oxides and PM_{10} particles) and with increased resistance to air pollution. To increase the resistance of plants to air pollution, environmentally friendly fertilizers containing biostimulants and phytohormones have been developed and tested; these help plants overcome abiotic stress and ensure long-term viability of existing and proposed urban greenery of various types in different locations using model areas in Ostrava. According to the dendrometric survey (height, crown projection area) and the determined species representation and health status, different types of urban greenery have different dendrometric parameters. Aerial orthoimages of vegetation, as well as a detailed ground inventory of this vegetation, were used to determine vegetation characteristics. Based on this inventory, the leaf area index and stand height were approximated in small detail. This enabled the modelling of pollutant capture by existing and proposed urban greenery in a detailed 1 x 1 m grid. Sensor technology appropriately placed near the greenery was used to monitor the concentrations of air pollutants and evaluate the effect of the existing and proposed green infrastructure on the local air quality. Given its simple installation and operation, sensor technology is a suitable additional tool for measuring pollutants and meteorological elements used together with the stationary measuring network.

Ostrava, the third largest city in the Czech Republic, is the capital of the Moravian-Silesian Region, lying in the northeast of the country, and it is also an important part of the Central and Eastern European industrial agglomeration with almost 5 million inhabitants living at a distance of 100 km in the Czech, Polish and Slovak parts of the agglomeration. Since the establishment of the first ironworks in 1828, Ostrava has become an important industrial centre of the country; however, the extent of industrialization and concentration of heavy industry in the second half of the 20th century exceeded the carrying capacity and caused serious damage to the environment, including enormous air pollution. Despite the restructuring of the sector and numerous effective measures adopted to improve the situation (resulting in a reduction of almost 90% of pollution), air quality is still one of the city's biggest environmental problems, and the city is one of the most polluted in Europe.

The long-term low air quality has lead the city and the region to implement various measures to improve the local situation. The CLAIRO project unifies the research activities of the three most important regional universities with the cooperation of public and non-profit institutions, while also involving the public, in order to transfer innovative approaches to the development of the city.

With reference to the measurement of significant pollutants PM_{10} and $PM_{2.5}$, analyses have shown that in the period from 2005 to 2014, the legal limit value for the annual average (40 μg m^{-3}) was often exceeded. In 2016, the limit of 50 μg m^{-3} for PM_{10} was exceeded on an average of 45.3 days out of 365. The level of pollution varied at each station (from 27 to 89 days a year). The highest average annual concentrations of PM_{10} were measured in eastern parts of Ostrava (Radvanice area), where the annual concentration of PM_{10} was around 42.6 μg m^{-3}. With $PM_{2.5}$ the situation is even more serious. The annual limit value (25 μg m^{-3}) was exceeded at all air quality monitoring locations in the city (total of 9 stations). The average annual PM concentration varied from 22.2 to 35.5 μg m^{-3} (26.82 μg m^{-3} on average).

Benzo[a]pyrene is the city's biggest problem. For many years, the limit value (1 ng m^{-3}) was exceeded in all places where the concentrations of this pollutant are measured. The situation is most serious in Radvanice again (with an average annual benzo[a]pyrene concentration of 9.3 ng m^{-3}). Given the seriousness of this problem, air quality is naturally Ostrava's priority number one. An in-depth analysis has shown that the main sources of air pollution in Ostrava are stationary sources (metallurgical and energy production), household heating sources and transport. In Ostrava, the fourth most important factor is cross-border pollution from the nearby industrial agglomeration of Katowice (Poland). The situation in Ostrava is worsened by the local climatic conditions. Particularly relatively long windless periods, which lead to lengthy inversions in the winter, increase pollutant concentrations regardless of the reduction in emissions. The monitored area of the project is located in two selected areas in the cadastral communities of Radvanice (715018) and Bartovice (715085) in the Ostrava agglomeration, as the most affected locations in terms of air pollutant concentrations.

The Radvanice area consists of four adjacent arable plots 2601, 2626, 2631 and 2632. This part of the monitored area is more diverse and richer in terms of species diversity. There are scattered solitary trees growing in small forest stands. The existing forest stands extend to the edges of the monitored area. Unlike Bartovice, this area also has herbaceous growth. The area has significantly more moisture, which is reflected in the occurrence of water loving tree species, especially in the surrounding stands, namely willows and alder trees. There are several technical elements here for air quality monitoring. The area in Bartovice consists of the western to southwestern edge of the industrial waste landfill on plot 1217. There are currently no technical or vegetation elements in this area. The area is completely empty and barren. Near the monitored area to the east, new woody vegetation elements are already being planted, and a field road leads to the west.

II. THEORETICAL BASES

1 GREEN INFRASTRUCTURE

Green infrastructure can generally be defined as a strategically planned network of high-quality natural and semi-natural areas with other environmental elements, designed and managed to provide a wide range of ecosystem services and biodiversity protection in rural and urban environments (European Commission, 2013). Green infrastructure is a spatial structure that provides the benefits of nature and aims to strengthen nature's ability to supply more ecosystem goods and services, such as clean air or clean water. This in turn helps improve the quality of life and well-being of people. Green infrastructure helps improve the urban environment during periods of climate change, it mitigates floods, increases carbon sequestration and prevents soil erosion (European Commission, 2013).

Green infrastructure consists of a wide range of different environmental elements that can occur to varying extents, from small linear elements such as hedges or green roofs to entire functional ecosystems such as intact flood plains, forests, peatlands and free-flowing rivers (European Commission, 2013). Each of these elements can contribute to green infrastructure in urban, peri-urban and rural areas. For example, an urban park within a city can be considered an integral part of green infrastructure if it removes air pollutants, cools the environment, absorbs excess water runoff, and offers an attractive outdoor space for recreation (European Commission, 2013). Fig. 1.1 shows how green infrastructure improves air quality and mitigates the effects of a heat island in a city.

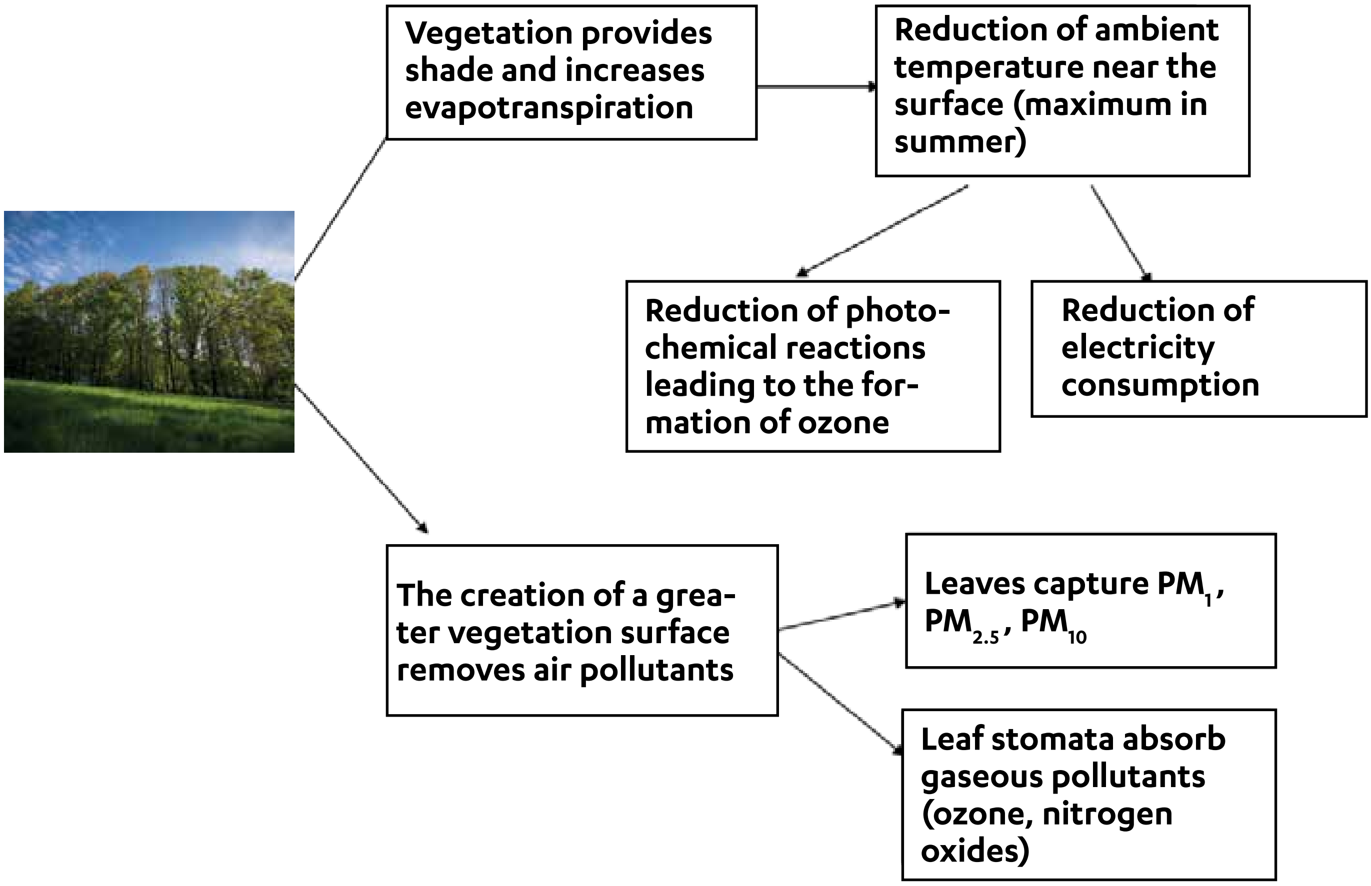


Fig. 1.1. How green infrastructure improves air quality and mitigates the effects of a heat island in a city.

2 CITIES AND GREEN INFRASTRUCTURE

2.1 SERVICES PROVIDED BY GREEN INFRASTRUCTURE IN CITIES

Almost 75% of the urban population in the EU is exposed to above-limit concentrations of PM_{10}, O_3, and BaP (WHO, 2015). However, despite significant investments in emission reduction, the extent of areas with deteriorating air quality varies considerably year-on-year, also depending on meteorological conditions. Poor air quality is associated with 400 000 deaths in the EU (EEA, 2012). Temperatures measured in cities are up to 12 °C higher than in the surrounding area due to the city's heat island. 75% of the EU population will be affected by increasing temperature stress (EEA, 2012). Mortality due to temperature stress is increasing (70,000 deaths were recorded in 2003). Green infrastructure (green roofs, green alleys and streets, gardens, plant boxes, green walls, bioretention systems, urban plant canopy) uses plants, soil and nature to reduce the impact of air pollution, urban heat islands and torrential rain to create a healthy urban environment. It increases the capture of air pollutants (aerosol particles PM_{10}, $PM_{2.5}$, nitrogen oxides, ozone) and carbon dioxide storage and increases the sequestration of carbon and water capture. It streamlines rainwater management and drought prevention. It reduces energy consumption in houses and subsequent impacts on carbon dioxide (CO_2) emissions, it cools the environment thanks to green roofs and walls combined with suitable materials for building and trapping pollutants (surfaces capable of binding and releasing water - wetlands, uncovered soil, vegetation, materials that reflect sunlight). Fig. 2.1 shows an example of a green roof, where one of the authors tested the capture of nitrogen oxides by grass at the Arctic University of Norway. Fig. 2.2 shows different types of plants on a green wall in Toulouse, France (Zapletal, 2017).

Fig. 2.1. Grass on the roof of a building of the Arctic University of Norway (photo by Miloš Zapletal).

Fig. 2.2. Different types of plants on a green wall in Toulouse, France (photo by Miloš Zapletal).

Cities are a place of life and human interaction. Today, more than half of the world's population lives in cities, and it is estimated that this number will grow to three-fifths of the world's population by 2030 (Fuller and Gaston, 2009; Smith and Guarnizo, 2009). The degree of urbanization in the Czech Republic is even higher. Over 73% of the population of the Czech Republic (over 7 million people) lives in urban areas (CZSO, 2018). Many of these people live in small or medium-sized cities with up to 50,000 inhabitants (over 42%). While cities connect us, their rapid and unprecedented growth has brought about serious challenges. Urban development has negatively impacted the environment, led to the loss of natural habitats and biodiversity, and increased the risk to human health associated with overheating, noise and air pollution. And we can expect the effects of environmental degradation to increase due to climate change. This is why we need to find ways to reduce health risks and maximize opportunities for high quality of life in ever-expanding urban environments.

Green infrastructure allows us to adapt conditions for a better life in the urban environment. In urban areas, green infrastructure can consist of green and blue areas such as parks, alleys, solitary street trees, green roofs, green tram lanes and green walls. These natural and semi-natural areas are strategically planned and managed to provide a range of ecosystem services.

Services provided by green infrastructure include:

- Population health: along with improved air quality, filtration of harmful substances, oxygen generation and noise absorption, green infrastructure helps prevent many diseases by encouraging inhabitants to engage in physical activity. Residents of green cities are more physically active and use various forms of sustainable transport.

- Resilience of cities: green infrastructure helps cities adapt to climate change and the associated increase in the frequency and intensity of temperature extremes, which affect the health of vulnerable groups. Green infrastructure can also prevent soil erosion, retain water in the landscape and reduce electricity consumption.

- Increased biodiversity: green infrastructure helps preserve and develop the number of species of animals and plants living in cities. Urban dwellers appreciate biodiversity; it also arouses interest in the environment and public space.

- Quality of life of residents: the amount of greenery is one indicator of quality of life. People in green cities are more active and satisfied, and greenery also helps prevent mental illness.

- Reduced stress: green infrastructure helps improve concentration, memory and learning ability, it has a calming effect and it speeds up recovery from illness.

- Attractiveness of the environment: green cities attract groups of people who are often more active, more enterprising, more educated, and more interested in the public space and events.

- Economic growth: green infrastructure creates new jobs and increases the value of housing and land. Green cities are more attractive to investors.

- Strengthened communities: green spaces invite people to meet. Projects such as community gardens and shared plants promote good neighbourly relations. Lower crime rates have been reported in green cities.

2.2 THE IMPORTANCE OF GREEN INFRASTRUCTURE IN PROTECTING HUMAN HEALTH

One important benefit of green infrastructure is its positive impact on human health and overall well--being. Green infrastructure provides a place for rest and recreation, as well as an environment for physical activities, which has a positive effect on our physical and mental health (Van den Berg 2015). The green space available near residential areas is directly related to lower obesity rates of the local population (Sakar, 2017) and a lower mortality rate due to cardiovascular diseases (Gascon et al., 2016).

The fundamental importance of green infrastructure from the perspective of human health is its ability to influence local microclimatic conditions and improve air quality. Main pollutants include ozone (O_3), nitrogen oxides (NO_x) and suspended particulates (PM_x), which have a negative effect on human health and vegetation. In 2005, 89% of the world's population lived in areas where the World Health Organisation's

Global Air Quality Guidelines were exceeded for at least one of these pollutants (Brauer et al., 2012). The World Health Organization estimates that suspended particulates contribute to approximately 800,000 premature deaths and the loss of 6.4 million years of healthy life each year (Brauer et al., 2012). Those most affected by air quality include our children during their most vulnerable stage of development (Landrigan et al., 1998). Compared to adults, newborns and infants breathe a larger amount of a combination of these pollutants, because they inhale more often than adults.

Green infrastructure improves air quality directly through vegetation cover, which removes air pollutants by capturing suspended particulates (PM_1, $PM_{2.5}$, PM_{10}) on the surface of leaves and pine needles, and gas molecules (O_3, NO_2) are absorbed through stomata. The amount of sedimented particles also depends on the size or mass of suspended particles and flow rate (Janhäll 2015). When particles settle on leaves, fine particles smaller than 1 μm can be further infiltrated through the stomata into intercellular spaces, where they can be further absorbed. A similar principle of absorption applies to tropospheric ozone particles. However, larger particles remain on the surface of the vegetation after their capture, from where they can be subsequently resuspended into the atmosphere, washed away by precipitation or deposited on the ground when deciduous leaves fall (Nowak et al., 2006).

Both mechanisms of air pollution reduction are conditioned by the structure of the vegetation growth. Important aspects include the shape and distribution of leaves and needles, as well as the roughness of their surface (Florentina and Io, 2012). It is not only the properties of plant organs and their arrangement that are decisive, it is also the overall structure of the vegetation, such as the height and density of the canopy, the shape of the crown and the spatial arrangement of the branches (Litschke and Kuttler, 2008). In general, the larger the surface area of the vegetation per unit area, the greater the capture of pollutants. This is why mature trees with a dense multilayer canopy are significantly more effective than low vegetation consisting only of a herbaceous layer (Lovett, 1994; Powe and Willis, 2004; Nowak and Heisler, 2010).

Green walls on high-rise buildings, so-called vertical gardens, can also significantly reduce pollutants (Pugh et al., 2012). In the streets of a densely built-up urban environment, we often see a phenomenon in which air flow is slowed down by the side walls of buildings, which leads to a greater concentration of airborne dust in the interspace. Strategic placement of these green walls can effectively capture this pollution. Planting greenery on roofs may have a similarly positive effect (Currie a Bass, 2008).

In addition, green infrastructure also affects the concentration of suspended particulates in the air indirectly by changing meteorological conditions. The main mechanism is a reduction of the air flow rate. Vegetation serves as an effective windbreak, where suspended particles are deposited on the ground and their overall concentration in the air is reduced on the leeward side due to a decreased flow rate.

Vegetation also modifies local temperature conditions. Daily temperatures are locally reduced primarily due to the limited amount of sunlight passing through the canopy and increased transpiration. Air temperature is a precursor to the formation of many pollutants. A drop in temperature reduces photochemical reactions leading to the formation of ground-level ozone. Locally reduced air temperature therefore partially reduces the concentration of pollutants in the air.

Last but not least, green infrastructure has a positive effect on human health by reducing stress and noise pollution (Al-Dabbous and Kumar, 2014). Greenery helps reduce the spread of noise by absorbing or scattering sound (Ten Brink et al., 2016). Spaces with greenery are also an important place for social events and activities, encouraging social interactions and community cohesion with a proven impact on human mental health (Dzhambrov et al., 2018).

3 THE QUALITY OF AIR IN CITIES AND ITS EFFECT ON HUMAN HEALTH AND VEGETATION

3.1 CHARACTERISTICS OF SELECTED AIR POLLUTANTS

3.1.1 SUSPENDED PARTICULATES (PM_x)

Dust particles in the air are solid or liquid particles that can be emitted directly from sources or formed in the atmosphere by reactions from precursor gases. Dust particles are divided into different groups depending on their physical and chemical properties; they are most commonly classified according to size. Fine particles (smaller than 2.5 μm) are formed in high-temperature processes (burning, smelting of ores, metals, welding) and photochemical reactions in the atmosphere. These are particles emitted from transport vehicles (vehicle exhausts) and industrial activities, and secondary aerosol, which is formed by chemical reactions from precursor gases (particles formed by oxidation and condensation of volatile organic compounds, sulphates, nitrates). Coarse particles (larger than 2.5 μm) are formed primarily by mechanical forces. In terms of dust from traffic, this fraction size is mostly dust from road erosion, tire wear, brakes and resuspended dust from the road surface caused by the passage of vehicles. Industrial activities that result in coarse particles include construction and mining activities, the production of cement and bricks, and fugitive emissions from the handling of dusty material.

Dust particles directly from sources are referred to as primary particles. Secondary particles are formed as a result of physico-chemical processes. Secondary dust are particles re-emitted from the earth's surface due to flow; sometimes the term resuspended particle is used.

Atmospheric aerosols typically have a diameter of 0.01 to 10 micrometres. Most aerosols are in the lower troposphere, where they remain for several days. They are washed out from the atmosphere by rain or snow. Larger particles settle due to gravitational force. Aerosols are composed of various substances and are of various origins. They come from rocks, soil, the sea, volcanic activities, industry (PAHs, heavy metals), transportation (PAHs, carbon black, rubber, resuspension), solid fuel heating (fly ash, carbon black, PAH). The physical mechanisms that have a decisive effect on the wet removal of substances from the atmosphere wash pollutants out from inside clouds as well as below the cloud layer. The main physical mechanisms include dissolution of gaseous components, oxidation of gaseous components, diffusophoresis, Brownian diffusion, impaction and condensation on condensation nuclei inside clouds. Dissolution and oxidation of gaseous components is particularly important for sulfur and nitrogen compounds. Diffusophoresis causes particles to move in the direction of the main flow of water or other vapour molecules. Brownian diffusion is only important for gases and the smallest particles. Impaction is an important process for larger aerosol particles. Condensation through condensation nuclei in clouds is the most important mechanism for the formation of aerosol particles.

Large aerosol particles (usually 1 to 10 μm in diameter) are formed by wind from sea salt, dust and other impurities emitted into the atmosphere. Fine aerosol particles with a diameter of less than 1 micrometre are primarily formed in the atmosphere by condensation of precursor gases. Important components of fine aerosols include sulfates, nitrates, organic carbon and elemental carbon. Sulphates, nitrates and organic carbon particles are formed by atmospheric oxidation of SO_2, NO_x and VOC. Elemental carbon particles are emitted during combustion. Combustion is also the main source of organic carbon particles.

Some aerosols have a cooling effect on the Earth's climate because they reflect sunlight back into space. Large eruptions from volcanoes emit large amounts of aerosols into the stratosphere, which can significantly reduce average global temperatures on Earth for a certain period of time. On the contrary, some aerosol particles, such as carbon black, absorb radiation and have a warming effect. Estimating the net direct contribution of aerosols to global climate change is a large scientific problem. This is why detailed inventories of individual types of aerosols in the atmosphere and their distribution worldwide are performed. Aerosol particles can also indirectly affect the Earth's climate, as condensation through condensation nuclei in the clouds creates clouds that reflect radiation back into space.

Measuring the concentration and chemical composition of particles is difficult, because the particles are difficult to capture without changing their chemical composition. Optical and mass spectrometric technology is used for the measurements, making it possible to analyse the chemical composition of individual particles directly in the air.

Organic aerosols are released into the atmosphere directly by combustion, or they are formed in the atmosphere from volatile organic compounds (VOCs) when their boiling point lowers. These are referred to as secondary organic aerosols. Cars, wood burned in furnaces, agricultural activities and the burning of forest stands are important sources of aerosols in the air. Atmospheric oxidation of anthropogenic and biogenic VOCs is an important source of secondary organic aerosols, especially in summer. The importance of these different sources of aerosols is still uncertain, which currently limits our ability to assess anthropogenic influences and develop strategies to reduce aerosol concentrations.

Transport and industrial activities are generally considered to be the main source of PM_{10}. Current information on chemical composition, size distribution, the proportion of secondary particles and the deposition flux of particles on different types of surfaces is still incomplete. Aerosol concentrations were measured in many cities at street level or for exposure assessment (Kaur et al., 2005; Longley et al., 2004). The eddy covariance technique was used to measure fine and ultrafine particle emission flux over large urban agglomerations, which provided information on upward airflow and vertical particle exchange over some urban agglomerations (e.g. Manchester, London, Helsinki) (Dorsey et al., 2002; Martin et al., 2009). The emission flux of particles over different types of sources at different heights above arable land with and without vegetation was measured using an airship Zapletal et al. (2019a) and a surface coal mine Zapletal et al. (2019b). These measurements provided information on the vertical profile of the concentration of particles and the emission and deposition flux of these particles over surfaces with vegetation and surfaces significantly affected by anthropogenic activity.

3.1.2 NITROGEN OXIDES (NO_x)

The term NO_x means a mixture of NO (nitrous oxide) and NO_2 (nitrogen dioxide). NO is generated as a product of imperfect combustion or some chemical-technological processes, and it is unstable in the atmosphere. The more stable NO_2 remains in the atmosphere for about 10 days. However, it all depends on the photochemical reactions in which the nitrogen oxides participate. The most significant source of NO and NO_2 is transportation, which is why the concentration of NO_2 is a major problem in all cities (EEA, 2012).

Nitrogen oxides are highly reactive gases that are formed by the reaction of oxygen and nitrogen at high temperatures during combustion or when lightning strikes. The nitrogen present in fuel can also be emitted as NO_x during combustion. Emissions are mostly generated by the combustion of fossil fuels in northern and central latitudes, and the combustion of biomass in tropical areas. The distribution of NO_x emissions into the atmosphere can be monitored by satellite measurements of the atmospheric concentration of NO_2. In the atmosphere, NO_x reacts with volatile organic compounds (VOCs) and carbon monoxide (CO) to form ground level O_3 through a complex chain reaction mechanism. This reaction mechanism eventually results in nitric acid (HNO_3), which, like H_2SO_4, contributes to the acidification of the environment and the formation of aerosols. There are several ways in which NO_x leads to the formation of HNO_3. The majority of NO_x comes from the combustion of fossil fuels (organic nitrogen in fuel) or the oxidation of atmospheric nitrogen (NO_2) in diesel engines (Warfvinge and Sverdrup, 1995). NO is also released from the soil after fertilization and subsequent exposure to bacteria.

NO_x goes through a number of reactions in the air. NO is generated at temperatures above 1000 °C and it oxidizes to NO_2 in the air by a spontaneous reaction. However, it can decompose photochemically into NO and oxygen (O). Most of NO_x eventually turns into the most stable form, namely HNO_3. The reaction between HNO_3 and alkaline dust particles produces solid particles that settle and are also washed out of the atmosphere by precipitation.

Over 90% of NO consists of NO_x emitted to the ground layer of the atmosphere. During the day it is quickly converted into NO_2. The conversion of NO_2 into HNO_3 is slow and it depends on the sun's radiation. It ranges from 2% per hour in winter to 30% per hour in summer.

The main emitted oxidized nitrogen compound is NO, which oxidizes in the atmosphere to NO_2 and further to nitrates. During the day, NO_2 oxidizes in the gas phase to HNO_3 by means of OH-radicals. NO_2 reacts with water absorbed on various surfaces to form HNO_3, and nitrous acid (HNO_2). HNO_2 is released from the surface, while HNO_3 remains absorbed. This provides less opportunity for nitrate formation in the aerosol (Hov et al., 1987). HNO_2 may also be formed through a reaction between N_2O and OH- (Pitts and Pitts, 1986). High concentrations of HNO_2 have been measured in some polluted areas in Europe, although HNO_2 photolyses very rapidly (Slanina et al., 1990). At night, NO_2 is oxidized by O_3 to form nitrate radicals, which can be a significant source of HNO_3. Unlike gaseous nitrogen compounds, HNO_3 has higher deposition rates and remains in the air for shorter periods.

Nitrogen oxides are involved in the formation of ground-level ozone and photochemical smog. A part of NO_2 reacts with nitric acid, which is contained in acid rain. Nitrogen that reaches the soil acts as a fertilizer, which is a positive effect. However, at higher concentrations it can be harmful. High concentrations of nitrogen in the water result in eutrophication, overgrowth of some aquatic plants and often the death of fish.

3.1.3 TROPOSPHERIC OZONE (O_3)

We have known of the existence of ozone in the troposphere for over 150 years. It is necessary to distinguish between the terms stratospheric ozone and tropospheric ozone, indicating which layer of the atmosphere they are in. Stratospheric ozone is beneficial to the Earth and to the existence of life on it, because it forms the ozone layer. Tropospheric ozone, on the other hand, is harmful. Under normal conditions, ozone is a blue reactive gas with a characteristic odour and extremely strong oxidizing effects. The occurrence of ozone depends on solar activity.

Ground-level ozone (O_3) is a secondary air pollutant that is toxic to humans and vegetation. It is formed in the troposphere through the oxidation of VOC and CO when NO_x is present. The mechanism is complicated, involving hundreds of chemical reactions that describe the degradation of VOCs. An important aspect of this mechanism is that NO_x and OH radicals act as catalysts. This means that they accelerate the rate of O_3 formation without being consumed by themselves. This mechanism of O_3 formation in the ground layer of the atmosphere is completely different from the mechanism of O_3 formation in the stratosphere, which contains 90% of the total atmospheric O_3 and plays a key role in protecting life on Earth from UV radiation. Stratospheric O_3 is formed by photolysis of oxygen. This process does not take place in the troposphere, because the strong UV radiation (<240 nm) needed to dissociate molecular oxygen is depleted by O_3 in the stratosphere.

O_3 is one of the strongest oxidizing agents. O_3 in the ground layer is formed in smaller amounts by oxygen photolysis, and it also enters it by descending from the stratosphere due to its higher specific gravity (about 10-15%). The majority of O_3 is formed in the troposphere indirectly by the effect of sunlight on NO_x with present VOCs. There are no significant direct anthropogenic emissions of O_3 into the air. The processes that produce and remove O_3, which involve the absorption of solar radiation by nitrogen dioxide, can be characterized by the following reactions:

$$NO_2 + h\nu \rightarrow NO + O$$
$$O + O_2 \rightarrow O_3$$
$$O_3 + NO \rightarrow NO_2 + O_2$$
$$NO_2 + O_2 \leftarrow NO + O_3$$

The presence of OH radicals and volatile organic compounds (VOCs) in the air, whether of natural or anthropogenic origin, causes a shift in equilibrium in favour of much higher concentrations of O_3. VOC include C6 - alkanes, aldehydes, ketones, various esters and chlorinated hydrocarbons. Many of these can be found in the exhaust gases of internal combustion engines and emissions from various chemical production processes, cleaning agents and solvents. In addition to O_3, other oxidants are also formed during photochemical processes, e.g. HNO_3, hydrogen peroxide (H_2O_2), secondary aldehydes, etc.

The maximum concentration of O_3 that can be reached in polluted air most likely depends on both the absolute concentrations of VOC and NO_x and their ratio. At medium values of the ratios of these concentrations (4:1 to 10:1), the conditions for the formation of high concentrations of O_3 are favourable. Because the ratios of VOC concentrations to NO_x concentrations in the air of a densely populated and heavily industrialized area of the Czech Republic don't change much, meteorological conditions in this area are the main factor determining the rate of photochemical processes (Grennfelt, 1984). Ozone concentrations are highest when children are outside the most (summer afternoon).

Concentrations of ground-level ozone depend on solar activity and they vary over the years, but it is still clear that especially in connection with frequent extreme temperatures, ozone concentrations also increase slowly in the long run. An analysis of spatio-temporal trends of long-term measurement at 26 different types of stations (urban, rural, mountain) in the period from 1994 to 2015 showed that despite a significant reduction in precursor emissions and reduced concentrations of O_3 in the air, O_3 still poses a significant problem at most stations in the Czech Republic (CHMI, 2019).

The presence of ozone in cities is undesirable because it can lead to photochemical smog, which contains a number of organic radicals that pose a significant risk to human health (for more details, see Hůnová and Bäumelt, 2018).

3.2 THE EFFECT OF SELECTED AIR POLLUTANTS ON HUMAN HEALTH AND VEGETATION

3.2.1 SUSPENDED PARTICULATES (PM_x)

There are a number of conclusive studies that show a connection between exposure to PMx and adverse effects on human health, particularly cardiovascular and respiratory diseases. According to the US EPA, these particles worsen respiratory problems (respiratory tract irritation, cough) and cause decreased lung function, asthma, chronic bronchitis, heart attacks, irregular heartbeat and premature death of people with heart or lung disease (US EPA, 2008). Other harmful substances can enter the body through suspended particles, e.g. polyaromatic hydrocarbons, heavy metals, dioxins. These substances may have carcinogenic, mutagenic or teratogenic effects and may increase overall mortality.

The main effect of these substances includes both acute manifestations - cough, acute respiratory diseases, mucosal irritations, worsening of existing respiratory diseases and cardiovascular diseases, increased hospitalizations and mortality, and chronic manifestations, namely diseases of the respiratory system (inflammation of the bronchi, lungs) and circulatory system, premature death, decreased lung function, allergies, asthma. They may also have carcinogenic and mutagenic effects - cancer, developmental defects.

PM_{10} - coarse dust particles (smaller than 10 μm) are retained in the upper respiratory tract; they can be swallowed, coughed out or sneezed out.

$PM_{2.5}$ - smaller particles (smaller than 2.5 μm) are gradually captured in the upper respiratory tract.

PM_1 - the smallest particles (smaller than 1 μm) penetrate deeper into the alveoli.

The population burden of solid, liquid or mixed suspended particles in a size of 1 nm - 100 μm is one of the biggest problems not only in the Czech Republic, but virtually in the whole of Europe. High particle concentrations result in health issues, including respiratory diseases and an increased risk of lung and skin cancer (WHO, 2006). High aerosol concentrations are a major cause of cardiovascular disease, and they can also cause cancer. Fine and ultrafine particles are especially dangerous, because they can be absorbed deep into the lungs and into the bloodstream. Scientific studies on the adverse effects of particles on human health have set limits for expo sure to particles with a diameter of 10 micrometers or less and for particles with a diameter of 2.5 micrometres or less. Aerosols also have significant radiation effects in the atmosphere. In the Czech Republic, long-term exposure to particles is a significant factor responsible for reducing the population's quality of life. One of the most serious effects in terms of overall health burden is a significant reduction in life expectancy (WHO, 2006).

The limit value for PM_{10} to protect human health is established as an annual average in the amount of 40 ug m^{-3}, or a 24-hour average of 50 μg m^{-3}, which may be exceeded 35 times a year. Tab. 3.1 shows limit values of PM_x for human health.

Tab. 3.1. Limit values for PM_x (CHMI, 2019) pursuant to Act no. 201/2012 Coll., on air protection, as amended, and Decree no. 330/2012 Coll., on the method of assessment and evaluation of ambient air pollution levels and on the extent of informing the public about levels of ambient air pollution and during smog situations.

Substance	Limit value (μg m^{-3})	Type of limit	Consequences of exceeding the limit
PM_{10}	50	24-hour	Increase in total mortality by 0.5% with an increase in the 24-hour average concentration of PM_{10} by 10 μg/m^3
PM_{10}	40	annual	Increase in total mortality by 3% with an increase in the annual average concentration of PM_{10} by 10 μg/m^3
$PM_{2.5}$	25	annual	Similar to PM_{10}

3.2.2 NITROGEN OXIDES (NO_x)

Nitric oxide significantly irritates the airways; it causes cyanosis and thus prevents the transfer of oxygen in the blood, when haemoglobin is converted to oxidized methaemoglobin. Even very low concentrations are irritating to the respiratory tract. Acute poisoning is manifested with a persistent cough, pulmonary edema or other lung damage. Methaemoglobin is formed in the blood, which is manifested by cyanosis (blue skin). In more severe cases, this leads to shock, convulsions, respiratory arrest and death (NIPH, 2019).

Nitrogen dioxide is an aggressive, highly toxic gas with a characteristic foul-smelling odour. It causes inflammation of the airways from mild forms to pulmonary edema. Nitrogen gases are suspected of being carcinogenic. They damage plants, contribute to smog and damage the ozone layer. Tab. 3.2 shows the limit values for NO_x for human health and vegetation.

Tab. 3.2. Limit values for NO_2 (CHMI, 2019) pursuant to Act no. 201/2012 Coll., on air protection, as amended, and Decree no. 330/2012 Coll., on the method of assessment and evaluation of ambient air pollution levels and on the extent of informing the public about levels of ambient air pollution and during smog situations.

Substance	Limit value (μg m^{-3})	Type of limit
NO_2	200	1 hour
NO_2	40	one year
NO_x	30	one year

The importance of nitrogen oxides lies in their participation in a number of reactions that lead to far more complex and dangerous molecules. The reason for their high reactivity is the formation of atomic oxygen with a free electron (radical), which is extremely reactive and reacts with organic substances that also have a free radical. These substances are suspected to have carcinogenic effects and are harmful to health. The effect of NO_x on the environment on a regional scale primarily includes the eutrophication of natural ecosystems, their acidification and photochemical pollution of the ground air layer.

3.2.3 TROPOSPHERIC OZONE O_3

Ozone is a highly toxic and reactive gas. Ozone is particularly harmful due to the formation of highly reactive free radicals (particles with an unpaired electron). It irritates the airways and may cause pulmonary edema. Decreased lung function occurs at a mean concentration of 160 μg m^{-3} lasting hours to days. It also has an adverse effect on the central nervous system, manifested by irritability, headaches and fatigue. Acute irritant effects include burning of the eyes, nose and throat, or chest tightness, cough and a headache (NIPH, 2019).

The limit value to protect human health is set as a maximum daily eight-hour moving average, and its value is 120 μg m^{-3}. The maximum number of exceedances allowed is 25, evaluated based on the average over three years. Tab. 3.3 shows O_3 limit values for human health and vegetation.

Tab. 3.3. Limits for tropospheric ozone (CHMI, 2019) pursuant to Act no. 201/2012 Coll., on air protection, as amended, and Decree no. 330/2012 Coll., on the method of assessment and evaluation of ambient air pollution levels and on the extent of informing the public about levels of ambient air pollution and during smog situations.

Substance	Limit (μg/m^{-3})	Type of limit
O_3	120	8-hour moving average
O_3 for protection of vegetation	6000	from 1h values (May - July)

Vegetation damage caused by O_3 was first observed in the 1940s in the area around Los Angeles, USA. Since then, ground level O_3 has been considered (if present in high concentrations) to be the most important phytotoxic pollutant in the air. Plants are particularly sensitive to increased concentrations, resulting in both chronic and acute damage. Ground level O_3 is believed to be a major factor contributing to the current forest die-off syndrome. Damage to agricultural crops caused by ground level O_3 is reaching significant economic proportions in various countries of the world (Europe, USA, Mexico, India) (Avnery et al., 2011). Losses on crop yields have been reported in these countries (Avnery et al., 2011). The negative effects of O_3 on crop yields have also been demonstrated in the EU (EP, 2002).

4 AIR QUALITY MONITORING

4.1 STATIONARY AIR QUALITY MEASURING NETWORK

There are currently two basic lines of air monitoring. Air quality is monitored by the Czech Hydrometeorological Institute (CHMI) in Prague as an organization established for this purpose by the Ministry of the Environment. The results are used to manage air quality in the Czech Republic and for all reporting. CHMI measurement has long been linked to the System of Monitoring the Environmental Impact on Population Health of the Czech Republic, which is implemented by the National Institute of Public Health (NIPH) and Health Institutes (HI) authorised by the Ministry of Health. The systems work together, sharing data with each other.

All information is available on the CHMI website, and partial information can be found on the websites of Health Institutes and NIPH Prague. In addition to CHMI, HIPH and HI, cities, regions, private companies and other entities also carry out monitoring.

Basic air pollution monitoring is performed by CHMI. The monitoring results are used by the Ministry of the Environment to manage air quality through resource regulation. According to the measurement principle, there is automatic air pollution monitoring (APM) and manual air pollution monitoring (MPM) (CHMI, 2019).

AIM is based on continuous measurement by stationary automatic analysers, usually with direct data transfer. APM measuring stations are usually equipped with analyzers that measure concentrations of SO_2, NO, NO_2, O_3, CO and suspended particulates PM_{10}, or $PM_{2.5}$. Almost all stations simultaneously monitor meteorological parameters - wind speed and direction, temperature, pressure, humidity.

MPM is mostly performed for substances that need to be analysed in the laboratory. Particularly organic substances require manual collection.

4.2 SENSOR TECHNOLOGY

Due to low financial costs and simple installation and operation, sensor technology for measuring the concentrations of air pollutants and meteorological elements is a suitable method to complement a stationary measuring network. Spatial data on pollutant concentrations and meteorological elements measured by sensors can be used to model the capture of pollutants by urban greenery and to analyse and evaluate urban greenery and the ecosystem services it provides. The capture of a pollutant in a given place during a certain period of time (e.g. vegetation period) can be calculated from the amount of air pollutants (dust particles, ozone, etc.) captured by vegetation in a certain area and time period, the deposition flux of air pollutants, the total vegetation area and time period. If there is no traffic in the street, vegetation captures the highest amount of pollutants. If there is a source of pollution in the street, then it depends on the correct distribution of the trees so that the capture of pollutants is not reduced by limiting the pollutant dispersion. When not distributed correctly, trees may contribute to pollution. Wind speed and direction have a critical effect on the trees in an urban canyon. When the direction of the wind is parallel to the direction of the urban canyon, the presence of trees reduces the concentration of pollutants. These accurate measurements of air pollutants in the urban environment require a large number of monitoring points, so it is best to perform these measurements with low-cost sensors. Meteorological parameters and pollutant concentrations measured by sensors enable optimization of tree and shrub planting. These sensors respond quickly to the current meteorological and environmental situation, and with models of dispersion, deposition, capture and resuspension of pollutants, they allow accurate areal evaluation of changes in the concentration and direction of pollutant spread. This enables optimization of the spatial planting of trees. The deposition and capture of pollutants are significantly affected by the type of surface. Leaving aside the possibilities of reducing the emission of air pollutants (dust particles, ozone, nitrogen oxides, etc.), we have the option of reducing these pollutants by capturing them through vegetation. The evaluation of urban greenery includes recommendations for urban planners on where to build buildings intended for sensitive populations and how to plant urban greenery and increase the capture of suspended particulates PM_{10}, ozone (O_3) and other air pollutants by vegetation in the urban environment. It is possible to determine the vegetation area that is able to absorb the required amount of the listed substances emitted by any source of air pollution.

Affordable, small and easily transferable sensors (microsensors or small sensors) for measuring air quality can generally be divided into several categories based on their method of measurement, namely electrochemical (for gases NO_2, NO, SO_2, O_3, CO), metal oxide (for gases NO_2, O_3 and CO), photoionization (for VOC), or optical particle counters (for PM_1, $PM_{2.5}$ and PM_{10} aerosoles) (Gerboles et al, 2017; Lewis et al., 2018). Although these inexpensive tools are relatively promising in terms of data retrieval from previously uncovered locations (both horizontally and vertically) and can thus be used to thicken official national monitoring networks or identify new hotspots (Kumar et al., 2015; McKercher et al., 2017), they also have their pitfalls, which must be taken into account when evaluating the measured data (Bauerová and Keder, 2019).

Sensor technology is one of many modern technologies. How it works, what it can measure and how accurate it can be is a matter of appropriate application settings. Fig. 4.1 shows a CO sensor and a multifunctional device for measuring up to 6 substances.

Fig. 4.1. CO sensor and a multifunctional device for measuring up to 6 substances.

The first sensors for measuring air pollution appeared 20 years ago. However, an attempt to miniaturize the measurement resulted in reduced reliability and accuracy of the device. The first sensors were therefore used to measure higher concentrations, especially in work environments. The first mass-deployed applications are carbon monoxide (CO) sensors in mines, as well as in houses and flats. The purpose of the CO sensor was to monitor the concentration of CO to prevent human poisoning. A sensor application for methane (CH_4) was developed almost simultaneously; it measured the concentration of methane together with oxygen (O_2) in mines, monitoring explosiveness or flammability. There are many types of sensors and practical applications that utilize them (Gerboles et al., 2017).

Thanks to the availability of sensors, it makes sense to connect them in networks and monitor the area of interest closely. The data measured by the sensors allow us to analyse pollutants closely, e.g. from an industrial zone, a road network or an industrial plant. Sensor networks make it possible to measure a large number of values and are therefore equipped with their own intelligence. There are examples of sensors connected to neural networks. The resulting models of measured concentrations allow us to explain the current air pollution, as well as to estimate the future development of its quality.

4.3 ELECTROCHEMICAL SENSORS

An electrochemical sensor is actually a cell with electrodes immersed in a gel electrolyte, which is separated from the external environment by a diffusion membrane. Gas molecules pass through this membrane and redox processes take place in the electrolyte, resulting in a change in the electrical potential of the cell. The electrodes gradually dissolve and the life cycle of the cell is limited.

Electrochemical sensors are usually very selective - they measure the monitored substance, they require very little energy for operation and they have a normal service life of about 1 year. The price depends on the type of sensor, usually ranging from 5,000 to 30,000 CZK. Today, the devices are designed so that

Fig. 4.2. Example of electrochemical sensors.

only the cell can be replaced at the end of its service life. Electrochemical sensors are among the most widespread, and their quality continues to increase while their price drops. Fig. 4.2 shows an example of electrochemical sensors.

The sensor operates by changing the resistance of the semiconductor, on the surface of which the measured substance is absorbed. Unlike electrochemical sensors, a semiconductor is not depleted and it lasts for decades. Today there are applications for over 150 substances. The advantage of semiconductor sensors is their higher sensitivity and detection of even low concentrations of measured substances. However, due to the way they work, they are less selective than electrochemical sensors. Fig. 4.3 shows examples of semiconductor sensors for measuring gases and infrared sensors.

Fig. 4.3. Examples of semiconductor gas sensors (left) and infrared sensors (right).

These sensors use the ability of some molecules (CO_2, CH_4, NO_2) to absorb red light, causing the molecules to vibrate. The vibration level is measured. These sensors are very selective; they can work in an oxygen-free environment, but they are more expensive.

4.4 DESIGNING A SENSOR NETWORK IN A CITY

Designing a sensor network consists in selecting locations for the installation of a set of sensors (in cooperation with the city's representatives) so that indicators are measured in parallel with the monitoring of basic climate indicators (micrometeorological stations), which are used in the primary evaluation of measured values to eliminate error fluctuations of the measured values due to the influence of climatic phenomena.

A network of sensors for measuring air pollution in the monitored area should enable measuring the concentrations of PM_1, $PM_{2.5}$, PM_{10}, NO_2, O_3 and meteorological parameters with respect to both existing urban greenery and the proposed greenery. The sensor station should be equipped with an internal data logger, which allows data storage in the device, subsequent data download via USB connection and data visualisation using advanced software.

Due to the fact that the measured monitored data can be transmitted from the station in almost real time and stored in a database with an online platform, users will evaluate and process current data on air pollution.

The sensor system should contain protective housing – with wireless communication for online data transfer. The system should contain an integrated battery for autonomous operation and a GPRS module (1 M2M SIM card), and it should allow the connection of a solar panel. According to the current specific conditions, some boxes should contain sensors for measuring meteorological parameters: wind speed and direction, air temperature, air humidity, global radiation.

Stations should be able to measure low concentrations (ppb) with a preset time step of 1 minute. The device must be calibrated 1x per year. According to European legislation, the device must meet the parameters for indicative measurement (with a maximum error of +/- 30% pursuant to 2008/50/EC).

The data logger should transfer the data to a server, which should be accessible via a web application that allows data viewing and export to xls. The GPRS module must contain a SIM card for online connection. Data can be sent to a server using SW Visualis. The sensors can be equipped with an Arduino board (with data storage on an SD card). The sensors should allow disconnection from the station and separate use, as the sensor contains an internal battery that is sufficient for short-term measurements. These requirements are met by CAIRPOL. Data from sensors and meteorological sensors should be collected in an integrated data logger and sent through the network to the city's environmental database.

Sensors for individual substances should be delivered calibrated, which means they must have a verified and preset correction factor for all measured substances. The correction factor should be calculated after at least two days of comparative measurement with a reference device meeting the conditions for sending data to the ISKO system (the device must comply with European standards for measuring the given substances and must be properly calibrated; the device operator must be either authorised or accredited for air quality measurement). A separate factor is required for each substance (type of sensor). This comparison and establishment of validation factors should be performed by the supplier at his own expense, and he should give the contracting authority a report on the implementation of the assessment when the equipment is installed.

The comparison consists in performing comparative measurements using selected air quality measuring devices at the stations of the state reference network. In order to be able to identify defective sensors and validate different units with each other, all sensor units should first be placed in one location near the measuring devices of the reference network. The mutually validated sensor units should then be further compared with measurements at stations of the state reference network, which will allow determining correction factors and installing the units in areas of interest. The correction factors found in this comparative measurement will subsequently be used to validate the data measured by the sensor units.

5 EMISSIONS, TRANSFER AND DEPOSITION FLUX OF AIR POLLUTANTS

Green infrastructure is generally considered to be beneficial for air quality (Willis and Petrokofsky, 2017). However, the relationship between vegetation and air quality is complex. For descriptive purposes, the potentially beneficial effects of vegetation on air quality are generally divided into categories according to the processes of atmospheric deposition and atmospheric dispersion. In accordance with the complex dynamics of the system, the collective impacts of these processes are diverse, depending on the context of related phenomena on different scales.

In the processes that substances undergo in the atmosphere, from the initial emission of a substance from a source, through long-distance transfer and distribution due to meteorological processes, to transformations due to chemical reactions, atmospheric deposition significantly reduces the amount of substances in the air. As a result of a number of processes collectively referred to as deposition, there is no accumulation of substances in the atmosphere, they are here in a state of dynamic equilibrium. Atmospheric deposition contributes to the self-cleaning of the atmosphere: it removes substances that are emitted into the atmosphere or that are formed there as a result of chemical reactions. However, for other components of the environment (hydrosphere, pedosphere, biosphere), it is often a very significant source of pollutants (Zapletal, 1997).

Chemicals are released into the atmosphere by a number of sources. Anthropogenic emissions come from human activities such as fossil fuel combustion, industrial production, transport, agriculture. Emissions are generated during the formation of final products, auxiliary compounds and intermediate goods are the result of photochemical reactions in the atmosphere. These are both organic and inorganic substances.

Biogenic emissions are produced by natural functions of biological organisms, such as microbial degradation of organic materials. Emissions can come from natural sources, particularly volcanic eruptions, geothermal activity, fires, hurricanes and desert dust. These are also both organic and inorganic (Zapletal, 1997).

Many chemical reactions in the atmosphere create, adapt and consume chemical pollutants. Wind can carry pollutants far from their sources, so emissions in one area can affect components of the environment very far away from the source of the emissions. The long-distance transmission of pollutants complicates efforts to control air pollution, as it can be difficult to distinguish the effects of local emissions from those from remote sources. This makes it hard to identify the polluter who should bear the cost of reducing emissions.

Pollutants in the atmosphere return to Earth either because they are directly absorbed by a receptor (e.g. soil), as part of a chemical reaction (such as photosynthesis), or because they are deposited on Earth by rain, snow or fog. A diagram of the processes air pollutants are subject to is shown in Fig. 5.1.

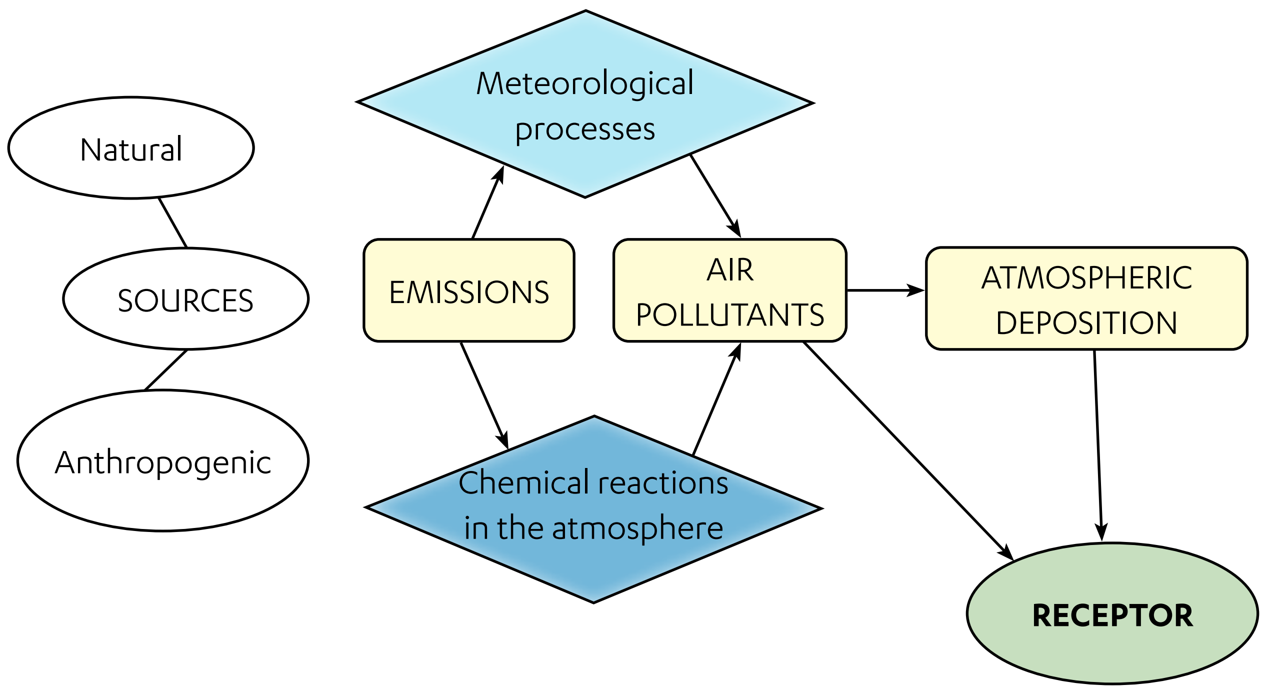


Fig. 5.1. Diagram of the processes air pollutants are subject to (according to Hůnová, 2003).

Air pollutants remain in the air for 1 to 3 days, and the average wind transmission distance in the atmosphere is 500 to 1000 km per day. Acidification is a regional problem associated with the long-range transmission of acidifying pollutants across national borders, and its reduction requires international efforts (cleaner fuels, reduced emissions).

Air pollution is strongly influenced by atmospheric conditions such as air temperature, air pressure, humidity, wind speed and direction, and global radiation. For example, wind carries some pollutants far from their source across state borders and across oceans. Transmission is fastest on the east-west route. Winds blowing in this direction can move air around the globe in a matter of weeks. Over the course of a few months or longer, pollutants can be transferred by air exchange in a north-south direction (Zapletal, 1997).

Local meteorological conditions significantly affect air pollution in a specific local area. Rain and snow transport pollutants through the atmosphere to the Earth's surface. Temperature inversion, which was also behind the great smog in London in 1952, occurs when the air near the Earth's surface is colder than the air at a higher altitude. Cold air is heavier than warm air, so the temperature inversion limits vertical air mixing and pollutants are kept close to the Earth's surface. These conditions often arise on winter nights. Light winds in the summer can lead to the accumulation of pollutants above the Earth's surface for several days. There are a number of places in the world where the links between weather conditions and air pollution along with specific orographic conditions (e.g. valleys surrounded by mountains) cause serious air quality problems. These are primarily urban or industrial areas. Emissions of air pollutants from small sources usually have a relatively low buoyancy, because the temperature at the point source is not much higher than the ambient air temperature (Zapletal, 1997). Emissions from these sources mostly affect the concentration of air pollutants is the area surrounding the source. Emissions from large and medium-sized industrial sources have higher temperatures and rise faster. Emissions from these sources affect the level of air pollutant concentrations at greater distances from the source and over large areas. Tall chimneys help to reduce emission concentrations and disperse them over a large area. Tall chimneys are generally used for power plants and other major industrial sources. Air pollutants emitted from these sources are carried over long distances, often across national borders, and are deposited far from their source (Zapletal, 1997).

There is usually no direct relationship between the amount of emissions emitted into the air by individual sources of pollution and the resulting air pollution concentration in the area. There is also no direct emission-deposition relationship. Area sources (residential buildings and small point sources) only represent a small part (approximately 30-40%) of the total emission balance of a village or city, but they can account for up to 60-80% of air pollution concentrations. This difference is mostly due to the low chimneys of residential buildings, the low heat yield of the heat sources of these buildings, poor dispersion conditions in the village or in the city, and the orography of the terrain. In contrast, sources with tall chimneys (100-160 m) that produce a large amount of emissions and have a high thermal output are responsible for 10-20% of the air pollution load of a village or city. High pollution sources are not the main source of pollution in the given area; on the contrary, they significantly affect pollution in remote areas (Zapletal, 1997). Regional diversity of production and industrial resources, and millions of cars, produce significant amounts of air pollutants, leading to photochemical smog under certain conditions.

Atmospheric deposition refers to the transfer of substances from the atmosphere to the Earth's surface as they drop or are washed out, and through sedimentation processes from the atmosphere. Atmospheric deposition may result in negative effects and processes in an ecosystem. Negative acidification processes and eutrophication of soil and water bodies can result from the deposition of gases, aerosol particles and acid precipitation. Dry deposition is a process by which gases and aerosols are deposited directly into vegetation, soil or material. It has two main components: the absorption of gaseous components and the settling of solid particles. The Earth's surface and all objects on it absorb atmospheric gases to a variable extent. The deposition of solid particles is mostly associated with the gravitational sedimentation (fall) of dust and the largest aerosol particles. In contrast, small aerosol particles (smaller than 20 μm), like gas molecules, only adhere to the surface to a small extent; they are captured mechanically, by electrical or other forces, and are therefore only partially removed from the air. Wet deposition is the washout of pollutants during precipitation. It is primarily vertical: snow, rain, drizzle and other falling precipitation that brings a number of dissolved and undissolved substances, trapped dust and aerosol particles along with the water. A quantitatively less important type of wet deposition is deposited precipitation, primarily including glaze, hoarfrost and dew, or water deposited from fog and icing (Zapletal, 1997). Deposition processes are shown in Figure 5.2.

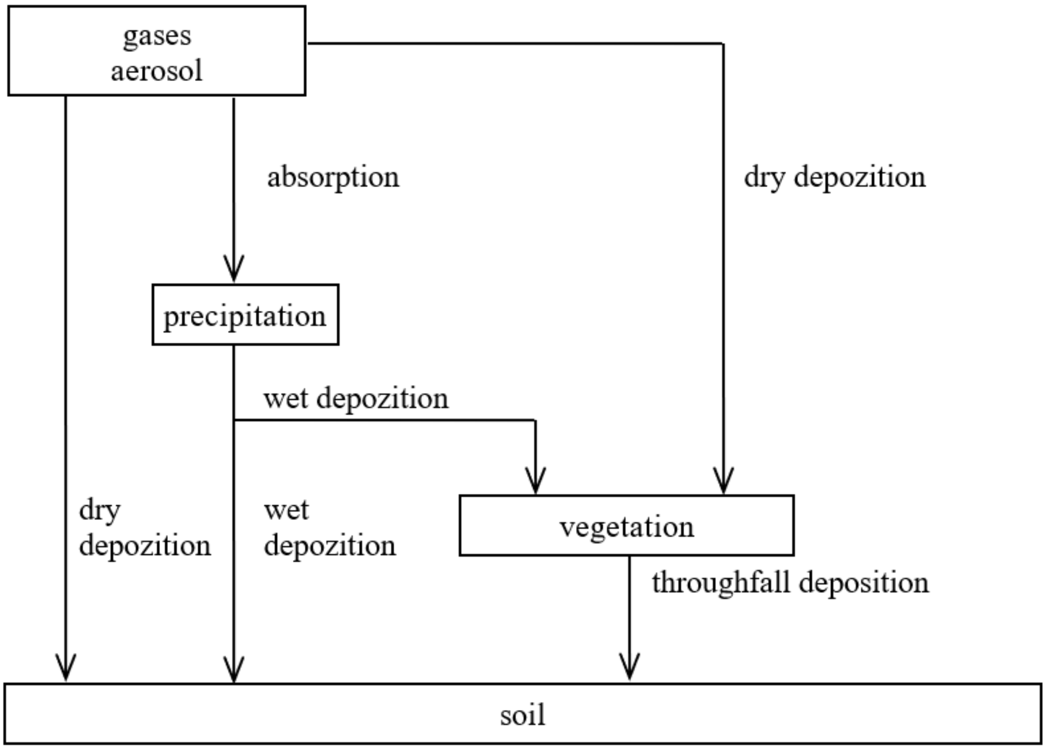


Fig. 5.2. Diagram of deposition processes (according to Erisman, 1992).

6 PRINCIPLES OF PLANTING GREEN INFRASTRUCTURE

The improvement of air quality through planting green infrastructure reflects a number of influences of individual types of vegetation and their structural properties. In addition to choosing the right environment, effective plant selection to reduce air pollution requires an understanding of the balance between beneficial and harmful aspects of vegetation at a species level. A summary of the individual steps of the process of designing green infrastructure with regard to the improvement of local air quality is illustrated in Fig. 6.1. The key properties of plants are described in the following chapters.

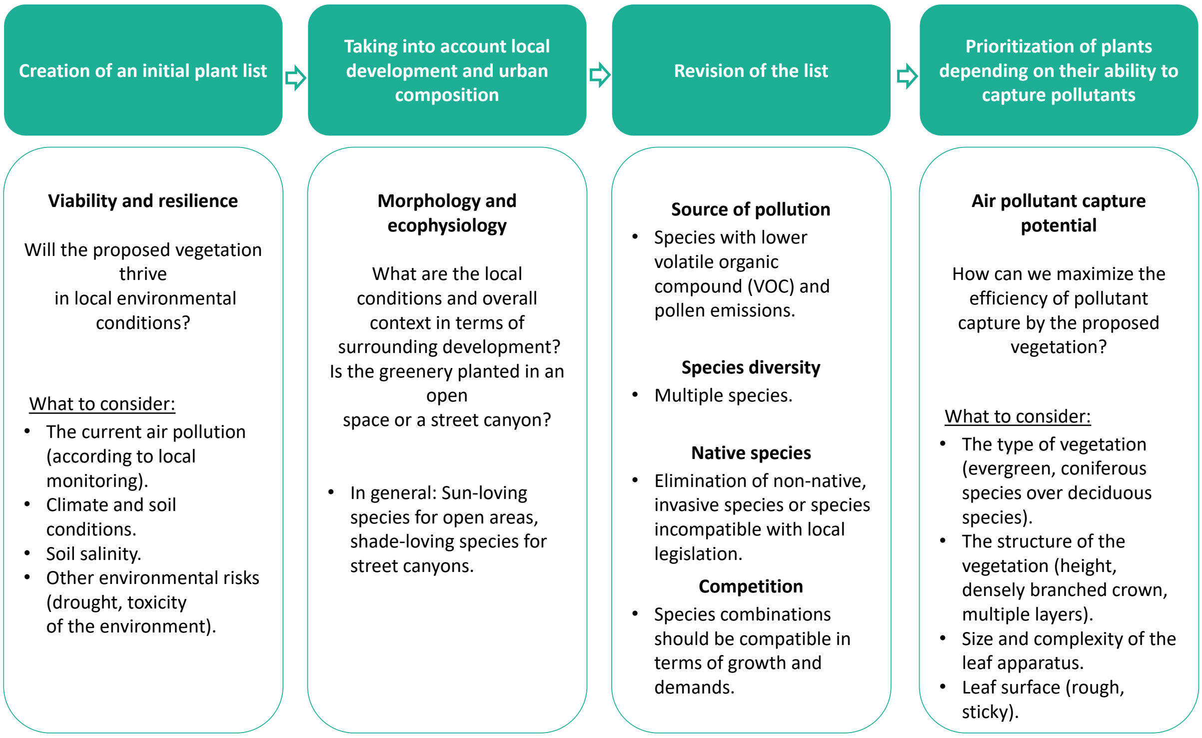


Fig. 6.1. Diagram of the procedure for creating a plan for planting green infrastructure with regard to improving local air quality. Edited based on Barwise and Kumar (2020).

6.1 FOLIAGE LONGEVITY

The foliage longevity describes the time during which the plant retains its green foliage. Evergreen species retain functional leaves throughout the year, while deciduous species function without functional leaves for part of the year, usually during the winter or drought. The foliage longevity varies between different species and genotypes, as well as environmental conditions. Given the importance of leaves in the deposition of pollutants, the foliage longevity is a crucial factor determining the effectiveness of green infrastructure in improving local air quality. Experiments have shown a significantly higher capture of pollutants on the surface of evergreen trees throughout the year compared to deciduous trees, which have a limited capture ability outside the growing season (Freer-Smith et al., 2005). Moreover, deciduous species that generally have longer leaf-on periods are more effective and should therefore be preferred over deciduous species with shorter foliage longevity (Sæbø et al., 2012). However, evergreen species may be more susceptible to certain stressors (e.g. global warming or acid deposition) than deciduous species, which may affect sustainable provision of ecosystem services (Seyednasrollah et al., 2018).

The timing of the leaf emergence itself, especially with regard to the seasonal variability of pollution concentrations, may be another important factor. Some species *(Faidherbia albida)* may experience reverse phenology, growing leaves during senescence (Roupsard et al., 1999). This property can be useful in reducing air pollution in winter, when pollutant concentrations are often highest (Sæbø et al., 2012), without having to limit the selection of potential species to evergreen ones. With knowledge of local pollutant fluxes, it is possible to select species according to the most suitable phenology, so that the green area is maximized during the period of highest pollutant concentrations.

However, selecting species based solely on phenology and the foliage longevity would not reflect the complex relationships between green infrastructure capture mechanisms and air quality, including other ecosystem services provided, such as microclimate regulation (Elmqvist et al., 2015). Moreover, pollutant capture efficiency likely also varies depending on the specific pollutant. In the case of tropospheric ozone, some studies point to higher efficiencies of deciduous species over conifers (Alonso et al., 2011). We can therefore assume that a combination of several deciduous and coniferous species with an overall higher species diversity is appropriate for a more efficient capture of a wider range of pollutants. This also increases resistance to seasonal weather fluctuations and long-term climate change.

6.2 LEAF SIZE AND SHAPE

Another important factor that determines the deposition of especially suspended PM_x particulates is the size and complexity of the leaf apparatus (Weerakkody et al., 2018). A number of studies have demonstrated that species with smaller leaves tend to be more effective than species with larger leaves. The higher circumference to surface ratio of smaller leaves may explain this (Neft et al., 2016). The needles of coniferous species generally appear to be very effective, providing higher deposition rates than the leaf apparatus of broadleaf species (Chen et al., 2017; Tallis et al., 2011; Viecco et al., 2018). Sæbø et al. (2012) explain that the long and narrow shape of the needles provides a thinner quasi-laminar boundary layer than leaf blades.

In the case of broadleaf species, pinnate and segmented leaf shapes are generally more effective than simple, entire leaves (Perini et al., 2017; Weerakkody et al., 2018). In the assessment of the properties of leaves for PM_x deposition, Weerakcody et al. (2018) state that complex (lobed, sinuate) leaf shapes show greater potential for PM_x deposition than simple (elliptical, round) leaf shapes. The authors suggest that differences in the efficiency of leaf shapes are associated with the flow of air around the leaf. The lower amount of captured pollutants on elliptical leaves despite their larger circumference is explained by their lower resistance to airflow, which can flow freely around the leaf with less tendency to create turbulent flow. A similar explanation may apply to the high capture efficiency of needles, which create an effective flow barrier with their shape. Wind tunnel experiments confirmed the high capture efficiency of some coniferous species (especially *Pinus nigra, Cupressocyparis leylandii*), yet not all coniferous species appeared so effective when compared to deciduous species (*Pseudotsuga menzeisii*). However, we can generally assume that needles and small, complex leaf shapes are more effective at capturing suspended PM_x particles.

6.3 LEAF SURFACE FEATURES

Another important factor influencing the efficiency of air pollutant capture are the properties of the leaf surface. However, the properties of the leaf surface can vary significantly not only between species, but also between individuals of the same species, depending on microclimatic conditions and other environmental properties (Grote et al., 2016), and the functionality of individual traits under any given circumstances is subject to internal or plant-specific factors, such as phenology, as well as external factors, such as ambient temperature.

In general, rough, hairy or glandular leaf surfaces are more effective at capturing pollutants than smooth surfaces with a more pronounced cuticle. For example, Weerakkody et al. (2018) listed a number of useful features for capturing PM_x, such as the presence of trichomes, epicuticular wax or surface ridges. Zhang et al. (2017) further reported a difference in the importance of individual traits in deciduous and coniferous species. While increased leaf micro-roughness (characterised by grooves and furrows on the leaf surface) in deciduous species correlates with increased deposition, the density of stomata and the amount of epicuticular wax are important in coniferous species.

6.4 STAND STRUCTURE AND DENSITY

The stand structure is an important factor determining the influence of the vegetation barrier on the movement of polluted air. This is determined by the properties of plant organs and their arrangement, as well as the overall connectivity and density of the growth, the height, crown shape and spatial arrangement of branches (Litschke and Kuttler, 2008). In general, the larger the surface area of the vegetation per unit of area, the greater the capture of pollutants. As a result, mature trees with a dense multilayer canopy are significantly more effective than low vegetation, consisting only of a herbaceous layer (Lovett 1994; Powe and Willis, 2004; Nowak and Heisler, 2010).

The density and connectivity of the growth is most often expressed by the leaf area index (LAI) or leaf area density (LAD). LAI is a dimensionless metric that describes the total leaf surface area per unit of area of the earth's surface (m^2/m^2) (Abhijith et al., 2017; Janhäll, 2015). In contrast, LAD describes the total unilateral leaf area per unit of canopy volume (m^2/m^3) (Abhijith et al., 2017). LAI and LAD are primary density parameters used to describe green infrastructure and its impact on pollutant capture (Janhäll, 2015).

In undamaged vegetation that is in good health, the structure and overall density of its growth is determined by the morphology of the leaf and the branching of the crown, which varies greatly from species to species. A recent field survey on the impact of green infrastructure on PM_x near roads found that pollutant concentrations generally decrease as leaf area density increases (Abhijith and Kumar, 2019). However, the results of other studies (Tong et al., 2016) suggest differences in the effectiveness of reducing pollutant concentrations depending on the size of the suspended particles. Abhijith et al. (2017) summarize that wide, tall and dense vegetation barriers in the direction of the predominant air flow reduce the concentrations of air pollutants. However, the relationship between vegetation density and capture efficiency is not linear.

The structural properties of the vegetation are not only determined by the selection of individual plant species, they also depend on the available planting space, the surrounding buildings and planning requirements. This demonstrates the contextual nature of planning the design of optimal green infrastructure.

6.5 POLLUTION TOLERANCE

The choice of vegetation species should further reflect the topographic, soil and climatic conditions at the site. The suitability of each species for the intended environmental conditions should be considered. The vegetation planting plan should take into account the sensitivity of specific species to air pollution in the given area, and it should be based on air pollution monitoring.

Concentrations of tropospheric ozone, sulfur dioxide and nitrogen oxides are important factors. Deciduous trees are generally more sensitive to tropospheric ozone than coniferous trees (Novotný et al., 2009). Experimental observations have shown relatively high sensitivity of cherry trees (Schaub et al., 2005), birch (Pääkkönen et al., 1998), alder and poplar (Skärby et al., 1998). Sensitive species of coniferous trees include Scots pine.

Another aspect that must be taken into account are the specific pedological conditions at the planting site. For example, many pine species are effective in capturing PM_x in the winter, but they are also prone to damage due to salinisation of soil during road treatments, which limits their viability. The use of alternative evergreen species that show salinity tolerance *(Taxus spp.)* may therefore be more appropriate for planting near roads (Sæbø et al., 2012).

6.6 SOURCE OF POLLEN AND VOLATILE ORGANIC COMPOUNDS

Despite the positive effects of green infrastructure on reducing the concentration of suspended particulates and the absorption of gases from the air, we should mention that vegetation itself can be a source of pollution. It produces pollen grains, which can cause allergic reactions, but they are generally less harmful to human respiratory health than similar exposure to PM_{10}, as the size of pollen grains is often larger. The main sources of allergens are *Fagales, Lamiales, Proteales and Pinales species*. Many commonly planted trees in urban environments belong to these orders, such as birch *(Betula spp.)*, ash *(Fraxinus spp.)*, plane trees *(Platanus spp.)*, and cypress trees *(Cupressus spp.)*.

Volatile organic compounds (VOCs) pose a more serious threat; they are emitted by vegetation into the atmosphere (Florentina and Io, 2012) and are associated with the formation of tropospheric ozone. Some of them are even small enough to cause the same health issues as suspended particulates (Litschke and Kuttler, 2008). The main sources of VOCs that we often encounter in parks include black tupelo *(Nyssa sylvatica)*, black locust *(Robinia pseudoacacia)*, populus trees *(Populus spp.)*, platanus trees *(Platanus spp.)* and oak trees *(Acer spp.)*. These negative aspects of vegetation must be taken into account in the selection of species. Nevertheless, it is generally assumed that the positive effect of greenery in reducing air pollution is prevalent.

6.7 DATABASE OF TREE SPECIES

Based on the above-described micro-morphological (at the level of individual plant organs) and macro-morphological (at the level of stand) traits, a list of selected tree species with higher resistance to air pollution and more efficient capture of pollutants was compiled (Table 6.1.). The whole plant database contains over 150 tree species and can be viewed on the CLAIRO website: www.clairo.ostrava.cz/know-how/. The trees are classified according to the type of leaf apparatus and natural occurrence (georelief and climate). The database contains both native and foreign species that are often planted in gardens and public spaces.

Tab. 6.1. Overview of selected tree species with regard to higher tolerance to acid deposition and higher efficiency of capturing suspended particles.

Latin name	Apparatus	Georelief	Climate	Sensitivity to acid deposition	Sensitivity to O_3	Ability to capture dust particles
Pinus nigra	evergreen	alpine	subtropical	resistant	tolerant	high
Picea abies	evergreen	mountain	boreal	sensitive	resistant	medium
Abies alba	evergreen	upland	mild	tolerant	resistant	medium
Quercus robur	deciduous	lowland	mild	resistant	resistant	medium
Quercus petraea	deciduous	highland	mild	resistant	resistant	high
Malus sylvestris	deciduous	highland	mild	resistant	resistant	medium
Ulmus minor	deciduous	lowland	sub-mediterranean	tolerant	tolerant	high
Cornus sanguinea	deciduous	highland	mild	tolerant	resistant	medium
Populus tremula	deciduous	highland	mild	resistant	resistant	medium
Prunus avium	deciduous	highland	mild	resistant	resistant	medium
Juglans regia	deciduous	upland	subtropical	resistant	tolerant	medium

6.8 COMPOSITION

The selection of the species themselves should also reflect the overall composition and connectivity of the individual elements of the green infrastructure.

In an effort to maximize canopy, the composition parameters of the species should take into account the ecological relationships of individual species and their demands on the habitat. The ideal composition is a combination of several layers with trees and a shrub layer in the undergrowth. The tree species composition should be spatially distributed so as to correspond to the position of the species in a natural community. Individual species mixtures should be compatible in terms of growth and demands. Individual layers should not compete with growth and aggression, and species in the undergrowth should tolerate shading.

7 TREATMENT AND FERTILISATION OF GREEN INFRASTRUCTURE

It is not only the species, structure and composition of the green infrastructure itself that determine the effectiveness of the capture of air pollutants; additional care and ongoing treatment are necessary to maintain the functions of the green infrastructure on a permanent basis. Trees and shrubs in good health will better photosynthesize and create a denser and better leaf area, which will subsequently have a positive effect on the capture of pollutants from the air.

Urban greenery is commonly treated with commercial inorganic fertilizers. However, the use of environmentally friendly products based on 'smart fertilizers' containing biostimulants and phytohormones, which help plants overcome various forms of abiotic stress, can be an innovative solution for both existing green infrastructure in urban areas as well as for treating new greenery in areas subject to a combination of different forms of abiotic stress.

Plant hormones (phytohormones) are small organic molecules that play a vital role in regulating plant growth and development. They occur naturally and act in small concentrations, forming in certain parts of plants, from where they are transported by the bast of the vascular bundle to their destination, eliciting a physiological response (Davies 2010).

The effect of the hormone must always be preceded by binding to a specific receptor. The function of phytohormones is non-specific; one hormone can affect multiple processes. In a mutual relationship, hormones can act in unison - synergistically or antagonistically - in opposition. Phytohormones are used as growth regulators in plant production and plant biotechnology. In high concentrations, they act as herbicides for weed control. The main groups of phytohormones are: auxin, cytokinins, gibberellins, abscisic acid, ethylene, brassinosteroids, jasmonates, strigolactones (Fig. 7.1) (Davies 2010).

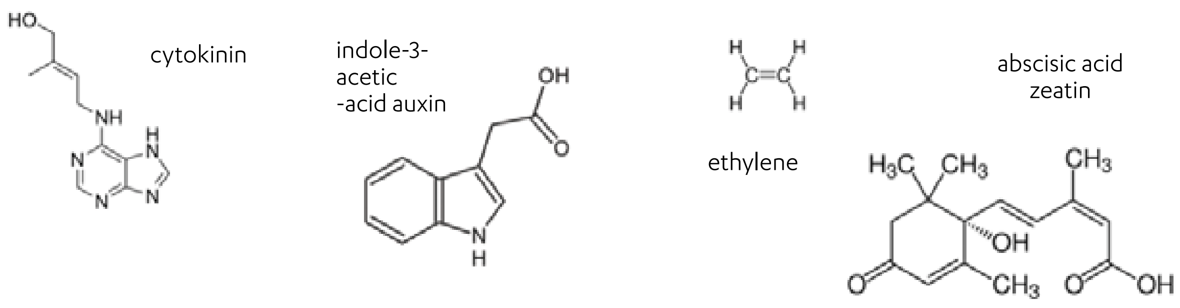


Fig. 7.1. Chemical structure of plant hormones.

Cytokinins (CK) are an important group of plant hormones. They were discovered in the 1950s in an effort to find substances that would stimulate the division of plant cells in tissue culture in the presence of auxin (Davies, 2010). This principle is successfully used in the development of cloning and micropropagation techniques for a large number of plant species that are economically significant or endangered. However, these substances also have a number of other functions: they support the growth of the above ground part of the plant, the growth of axillary buds, apical dominance, the development of chloroplasts and the delayed onset of leaf senescence. This may increase their resistance to various stressors. Cytokinins are therefore of great economic importance (Davies, 2010). Cytokinins affect these processes in cooperation with other plant hormones. All naturally occurring cytokinins are adenine derivatives substituted at the N6 position by an isoprenoid or aromatic side chain (Fig. 7.2) (Davies, 2010). In plant tissues, these signaling molecules are present in very low concentrations, which has made and still makes it very difficult to examine them. On the other hand, these substances or their related synthetic derivatives have been shown to have the ability to influence the growth and development of human tumor cells or dermal fibroblasts by a unique mechanism, thus having potential for a wide range of applications not only in agriculture and plant biotechnology, but also in medicine or cosmetology (Doležal and Strnad, 2017).

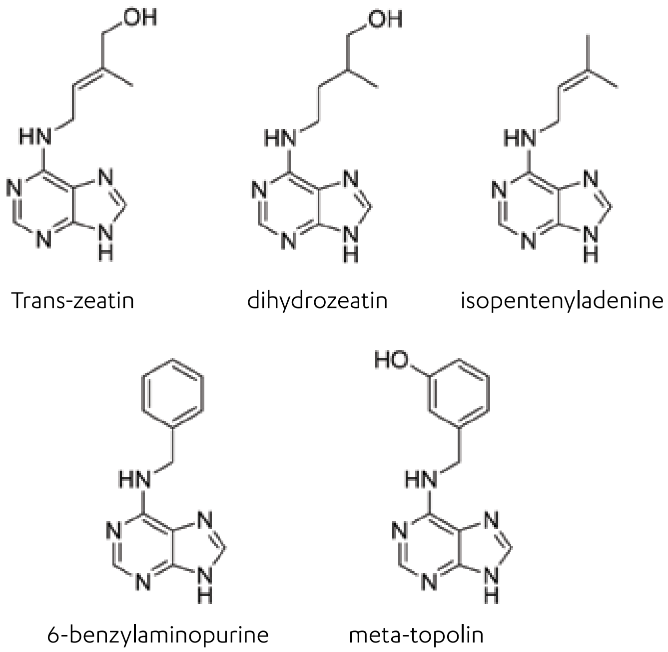


Fig. 7.2. Chemical structure of selected cytokines.

Biostimulants are biologically active substances obtained from natural or waste materials. They can support plant growth and/or strengthen the resistance of plants to various stressors. What makes biostimulants special is that they do not contain a high percentage of active substances, so they are not typical fertilizers or plant protection products. The active ingredients in biostimulants affect the metabolism of the plant and trigger processes in the plant that generally improve its growth and health. Interestingly, the exact mechanism of the action of most biostimulants is unknown, which opens up a number of possibilities for scientific research. Biostimulants may contain phytohormones, but this term is most commonly associated with protein hydrolysates, seaweed extracts, vermicomposts, and humic acids (Du Jardin, 2015; Calvo et al., 2014).

8 MODELLING OF POLLUTANT CAPTURE BY THE VEGETATION SURFACE

8.1 CALCULATION OF DRY DEPOSITION OF OZONE, NITROGEN OXIDES AND PM_{10} PARTICLES

A method that derives the deposition flux of components from the measured concentrations of these components in the air and their deposition rates was used to estimate the dry deposition of ozone (O_3), nitrogen oxides (NO_x) and PM_{10} particles according to the following relationship:

$$F = v_d(z).c(z), \quad (1)$$

where F is the deposition flux of the component, v_d is the deposition velocity of the component, and c(z) is the concentration of the component at height z above the surface. Concentrations of the monitored components in the air were measured by sensors.

A multiple resistance model was used to estimate the deposition rates of gaseous components (O_3, NO_x) from meteorological data and vegetation cover characteristics (Zapletal, 2001; Zapletal et al., 2011).

The deposition velocity v_d can be expressed as the inverse of the sum of three resistances:

$$v_d(z) = \frac{1}{R_a(z) + R_b + R_c} \quad (2)$$

and it can be calculated using a multiple resistance model that includes aerodynamic resistance (R_a), laminar resistance (R_b) and surface resistance (R_c). Aerodynamic resistance estimates the resistance to a deposition component during transmission at a certain height above the surface at which the concentration of this component is measured. Surface resistance R_c includes the plant canopy and soil. A diagram of the resistance components included in the deposition model is shown in Fig. 8.1.

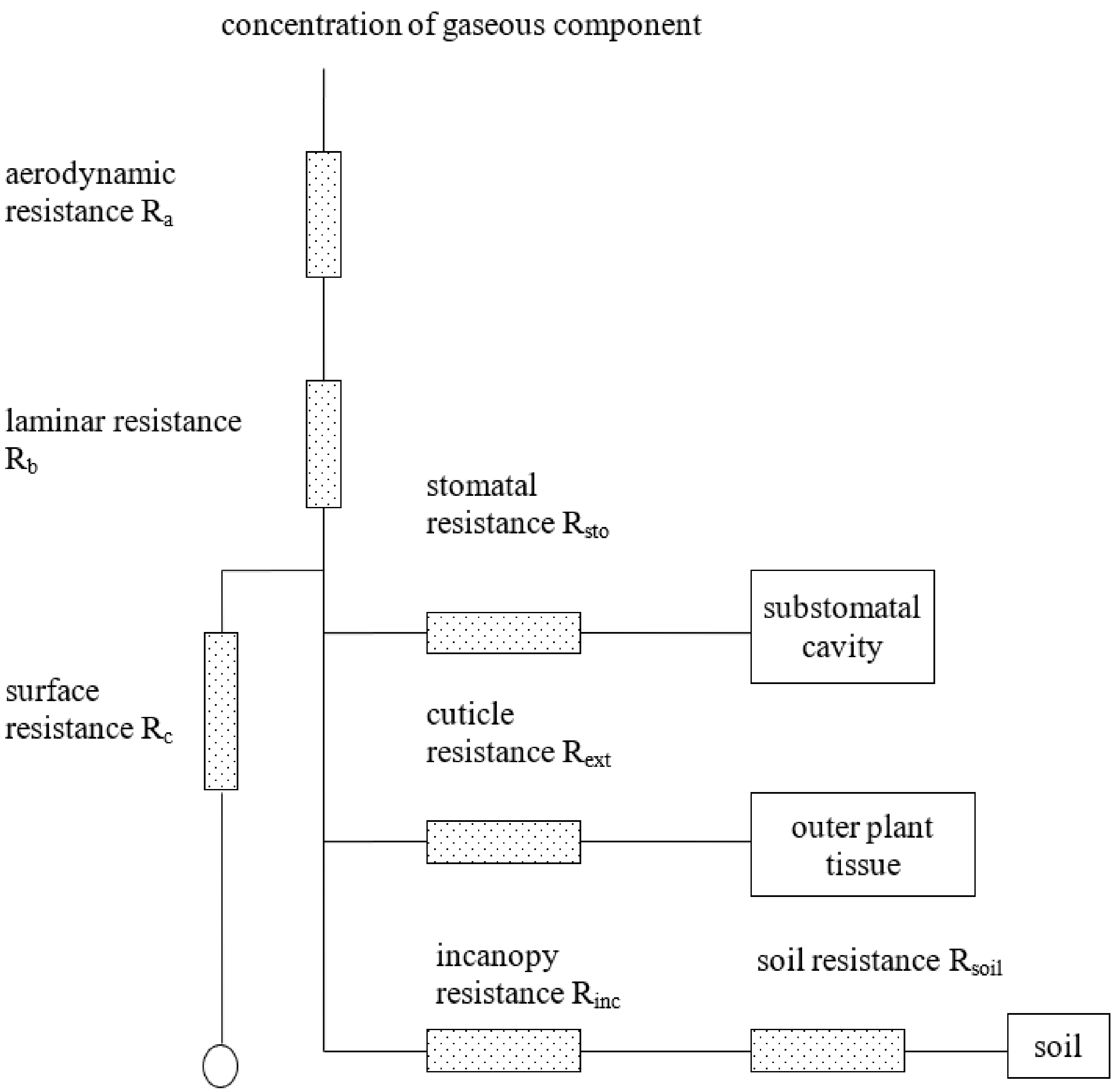


Fig. 8.1. Diagram of the resistance components included in the deposition model (Zapletal, 2014).

Aerodynamic resistance Ra was calculated according to micrometeorological relationships (Hicks et al., 1987; Hicks et al. 1989):

$$R_a = \frac{\ln\left(\frac{z}{z_0}\right) - \psi_c}{k u_*}, \qquad (3)$$

kde:

$$u_* = \frac{k u_z}{\ln\left(\frac{z}{z_0}\right) - \psi_m} \qquad (4)$$

k is von Karman's constant (0.4), u_* is the friction velocity, u_z is the horizontal wind speed at zero-plane displacement, z_0 is the surface roughness, ψ_m is the stability correction function for momentum, and ψ_c is the stability correction function for the pollutant concentration. For stable conditions of vertical atmospheric stratification (0<z/L<1), ψ_m and ψ_c were calculated using the following equation:

$$\psi_m = \psi_c = -\frac{5.z}{L} \tag{5}$$

in which L is the Monin-Obukhov length. For friction rate modelling, the ratio z/L = 0.03 was chosen, characterising stable conditions of vertical stratification of the atmosphere close to neutral conditions (Erisman, 1992). Laminar resistance R_b was calculated from an empirical relationship (Hicks et al., 1987):

$$R_b = \frac{5.\sqrt[3]{Sc^2}}{u_*}, \tag{6}$$

where Sc is the Schmidt number (ratio of kinematic viscosity of air to molecular diffusion of gas) (Hicks et al., 1987; Pul et al., 1995).

Surface resistance R_c is a function of stomatal resistance (R_{sto}), which is the resistance to the gaseous component during its intake by stomata, mesophyll resistance (R_m), canopy cuticle resistance or external leaf resistance (R_{ext}), i.e. the surface of leaves, needles, branches or the trunk in canopy resistance (R_{inc}), which is the resistance to the gaseous component in its transmission through the vegetation towards the soil and the lower parts of the plant canopy, and soil resistance (R_{soil}), which is the resistance of soil to the absorption of the gaseous component by the soil surface. Stomatal resistance, external leaf resistance and soil resistance act simultaneously.

The surface resistance R_c for O_3 was calculated according to the following equation (Emberson et al., 2000a):

$$R_c = \left(\frac{LAI}{R_{sto}} + \frac{SAI}{R_{ext}} + \frac{1}{R_{inc} + R_{soil}} \right)^{-1} \tag{7}$$

where (R_{sto}) is the land-cover specific leaf stomatal resistance to O_3 uptake;

(R_{ext}) is the canopy cuticle resistance or external leaf resistance, i.e. the surface of leaves, branches, the trunk;

(R_{inc}) is the land-cover specific in-canopy aerodynamic resistance to transport O_3 towards the soil and lower parts of canopy;

(R_{soil}) is the soil resistance, which is the resistance of the soil to the absorption of O_3 by the soil surface.

LAI is the leaf area index, SAI is the surface area index, which is equal to LAI in the growing season. Stomatal intake of O_3 (go_3 is the inverse of R_{sto}) was calculated according to Emberson et al. (2000c):

$$go_3 = g_{max} * g_{phen} * max\ [g_{min}, (g_{light} * g_{temp} * g_{VPD} * g_{SWP})] \quad (8)$$

where go_3 is the current stomatal conductance during site-specific climatic conditions, g_{max} is the average maximum stomatal conductance O_3 for the tree (mmol O_3 m^{-2} s^{-1}) expressed on the total surface of needles or leaves, parameters g_{phen}, g_{light}, g_{temp}, g_{VPD} and g_{SWP} are expressed in relative values between 0 and 1, representing the change in g_{max} during phenological changes, changes of light (μmol m^{-2} s^{-1}), changes in air temperature (°C), changes in vapour pressure deficit (kPa) and changes in soil water potential (Mpa), and g_{min} is the minimum stomatal conductance during the daylight period.

The values of the vapour pressure deficit were calculated according to an equation published by Buck (1981). The soil moisture deficit was estimated from precipitation and surface temperature according to the principles of water budget published by Mintz and Walker (1993). The physical soil parameters that are necessary to convert the volumetric soil moisture deficit to soil water potential were derived from a function published by Milthorp and Moorby (1974). All details of the parameters and functions that can be used to estimate the stomatal conductance of go_{3s} from environmental variables are listed in the work of Emberson et al. (2000a, 2000b, 2000c) and Wieser and Emberson (2003). R_{ext} = 20 s cm^{-1} and R_{soil} = 3 s cm^{-1} were used according to Brook et al. (1999). R_{inc} was modelled according to van Pul and Jacobs (1994):

$$R_{inc} = b\ LAI\ h/u_* \quad (9)$$

where LAI is the leaf area index; h is the vegetation height; b is the empirical constant 14 m^{-1} and u is the wind friction rate.

The stomatal flux of O_3 (F_{sto}) was calculated according to (Cieslik, 2004; Gerosa et al., 2009):

$$F_{sto} = \frac{R_c}{(R_a(z)+R_b+R_c)\ R_{sto}} c(z) \quad (10)$$

The total flux of O_3(F) was calculated from the measured concentrations of O_3 in the air multiplied by the corresponding deposition velocities according to equation (4).

The surface resistance R_c for O_3 was calculated according to the following equation:

$$R_c = \frac{1}{\left(\frac{1}{R_{sto} + R_m} + \frac{1}{R_{inc} + R_{soil}} + \frac{1}{R_{ext}}\right)} \quad (11)$$

Stomatal resistance (R_{sto}) was calculated according to Wesely (1989):

$$R_{sto} = R_i\{1+[200(G+0.1)^{-1}]^2\}\{400[T_s(40-T_s)]^{-1}\} \quad (12)$$

where R_i is the input resistance (s m^{-1}), G is global radiation (W m^{-2}) and T_s is the surface temperature (°C). The values of R_i were used according to Wesely (1989). The resistance in the plant canopy (R_{inc}) was modelled according to equation (12). Soil resistance Rsoil was calculated according to Meyers and Baldocchi (1987). The resistance of the outer plant surface Rext was chosen according to Erisman and Draaijers (1995). The average surface roughness z 0 values were taken from the work of Zapletal (1997).

The deposition rate of PM_{10} particles was calculated according to Fang and Wu (1999):

$$V_d = V_{st} + 1.12 \times u_* \times exp(-30.36 / Dp) \quad (13)$$

The friction velocity u_* (cm s^{-1}) was calculated according to equation (7). The particle settling velocity (V_{st}) PM_{10} is equal to 0.5 (cm s^{-1}) according to Fang and Wu (1999). Dp is the particle size (μm).

8.2 CAPTURE BY VEGETATION

Quantification of the capture (Q) of a pollutant in the given area over a certain period of time was performed according to Janhäll (2015):

$$Q = F \times LAI \times T \quad (14)$$

where Q is the amount of the pollutant captured by vegetation in a certain area and over a certain time period (g), F is the deposition flux of the substance (g m^{-2} s^{-1}), LAI is the leaf area index, i.e. the total vegetation area per unit of area (m^2 m^{-2}), and T is the time period (s).

In the capture of PM_{10}, resuspension was subtracted from the capture:

$$Q = Q - y \quad (15)$$

$$y = 0.0179^{\,0.2563*uz}, \quad (16)$$

where y is the amount of resuspended PM_{10} particles (g m^{-2}) and u_z is the horizontal wind speed (m s^{-1}) (Li et al., 2015).

8.3 DETERMINING STRUCTURAL PROPERTIES OF VEGETATION IN-SITU

As mentioned in the previous sections, one of the main variables that affects the deposition rate, the actual pollutant capture by vegetation, and ultimately the concentration of pollutants in the air, is the spatial structure of the vegetation cover. It is important to determine this factor in order to quantify the capture of pollutants, as well as to model various development scenarios, e.g. after the proposed greenery is planted (Currie and Bass, 2008).

The most commonly used indicator of the structure of the canopy is the leaf area index (LAI), defined as the one-sided area of a green leaf per unit of area of the soil (Watson, 1947). In coniferous trees, this refers to one half of the total surface area of the needles per unit of horizontal area of the terrain (Chen and

Black, 1992). The LAI is used to relevantly determine many biological and physiological processes within the tree layer, including interception, transpiration, and pure photosynthesis (Pierce and Running, 1988), quantification of the water and carbon cycle (Gower and Norman, 1991), and net primary productivity of the ecosystem (Gholz and Cropper, 1991). The LAI parameter has already been used in a number of case studies examining the capture of suspended PM10 particles and other pollutants by vegetation (Currie and Bass, 2008; Escobedo and Nowak, 2009; Tallis et al., 2011).

Methods for determining the LAI are traditionally based on ground measurements. Either direct, semi--direct or indirect measurements are used. Direct approaches involve calculating the total volume of leaf litter from collection traps (Vyas et al., 2010), or from the volume of artificially induced defoliation of green biomass from living trees (Hutchison et al., 1986). Although these are theoretically more accurate than other methods, because they are time consuming, destructive and they do not allow automation, they are used less and less (Jonckheere et al., 2004).

The transition between direct and indirect methods are methods that use other common parameters of forest inventory, from which they derive the properties of the canopy using allometric equations. The diameter of the trunk at breast height (DBH), or the height of the stand, the height of the base of the tree layer, and the average basal area are most often used (Jonckheere et al., 2004). Allometric equations are widely used to generalize and evaluate the LAI from the level of individual branches to entire stands.

Another approach are indirect methods, which, compared to direct methods, are non-destructive in nature but less accurate. These methods are based on mere approximations of empirically determined relationships between the optical properties of the canopy and its total area or volume (Jennings et al., 1999). These methods are not accurate for very dense and multi-layer canopies of tropical rainforests (Moser et al., 2007). To determine the LAI based on optical indirect methods, either the amount of light passing through the canopy is measured using pyranometers (Hassika et al., 1997), or hemispheric photographs are analysed (Fournier and Hall, 2017). The LAI is subsequently calculated on the basis of models using the Beer-Lambert law, i.e. the mathematical relationship between the absorption of electromagnetic radiation and the properties of the canopy. In contrast, the analysis of hemispherical photographs is a photographic technique using a wide-angle lens, allowing a 360° view of the canopy from the earth's surface (Fournier and Hall, 2017). The analysis of hemispherical photographs is based on the uncontrolled classification of a black-and-white image into two classes. According to the defined threshold, the individual pixels are divided into classes, one of which represents the visible surface (sky), while the other represents any physical obstacles (leaves, branches and tree trunks, surrounding terrain) that prevent the penetration of sunlight (Fournier and Hall, 2017). Their ratio determines the total coverage or openness of the tree canopy, from which the LAI is derived, as in radiation measurement (Fournier and Hall, 2017).

III. APPLICATION OF THE METHODOLOGY

9 INTRODUCTION

The aim of the application of the methodology was to evaluate and compare the air pollution load of ozone, nitrogen oxides and PM_{10} particles at two exposed locations in Ostrava Radvanice and Bartovice, both in the initial state without sufficiently functional green infrastructure, and with the proposed greenery after growth-balanced stages are reached in several species combination and structure variants.

Experimental investigation of environmental conditions in both locations was a means of verifying the function of greenery in the area of planting before the widespread introduction. The extent of the experiment was adapted to the prevailing growth conditions, including environmental burdens in the intended planting area. For statistically sufficiently probable verification, it is necessary to achieve a continuously connected stand. The experiment was performed as a comparison of the initial state without a sufficiently functional green infrastructure with the change after growth-balanced stages are reached in several species combination and structure variants.

10 DESCRIPTION OF AREAS OF INTEREST

The monitored area used for the case study is in two selected locations in the cadastral areas of the city districts of Radvanice and Bartovice (Fig. 10.1). These sites are characterized by significant emissions from the nearby industrial area in Ostrava Kunčice.

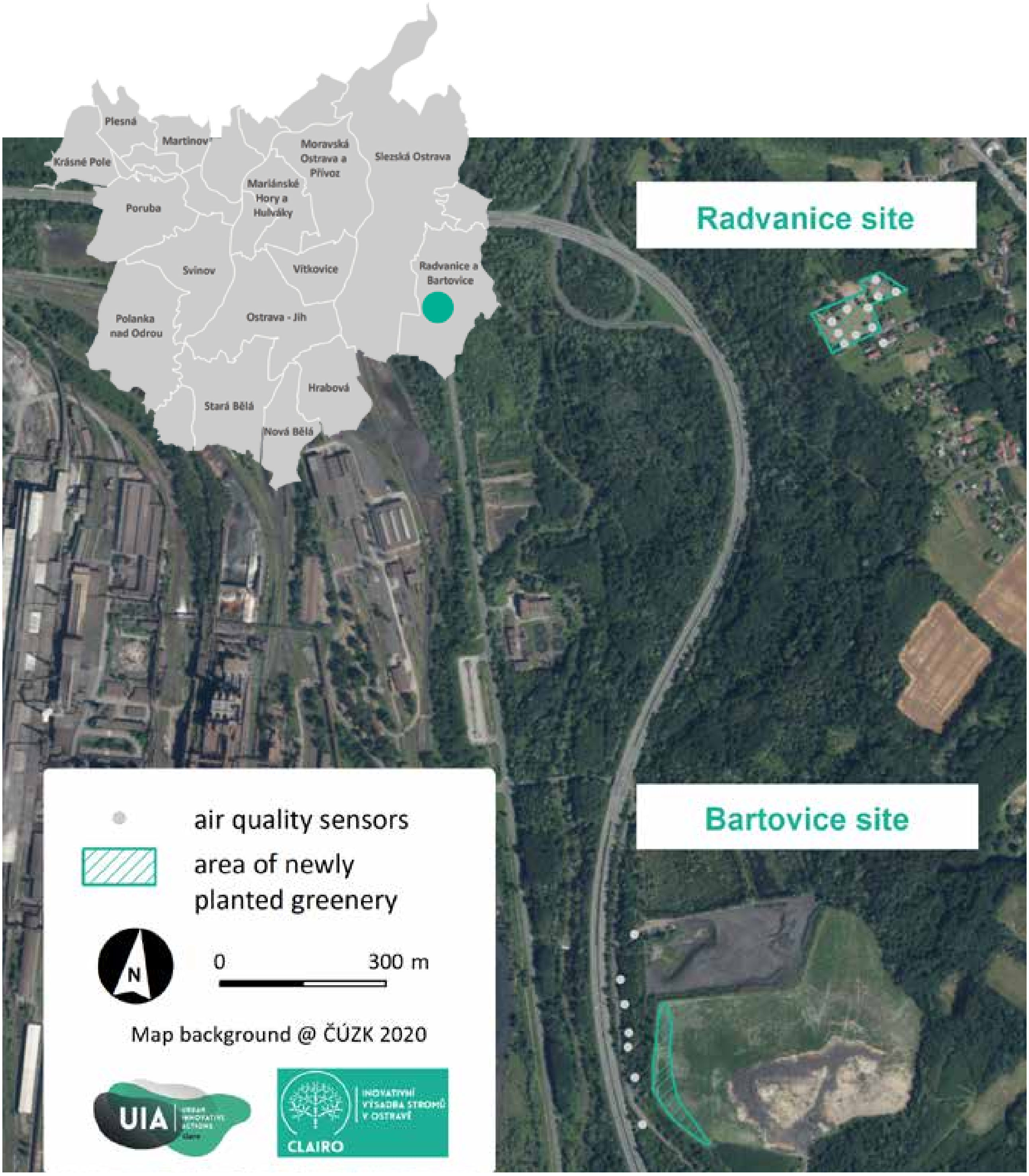


Fig. 10.1. Overview map of the areas of interest in the case study and the surrounding area; in the western part we can see an industrial building in Ostrava Kunčice.

Radvanice (Fig. 10.2) is spread over an area of 1.04 ha, and it includes a combination of permanent grassland and scattered, solitary trees and shrubs or their smaller clusters. The existing forest stand extends into the monitored area. The area is humid, which is reflected in the occurrence of moisture-loving tree species, especially in the surrounding stands, namely willows and alder trees. The area is open, with tall trees on the edges and 3 houses nearby. There is no barrier to the wind flow through the meadow, predominantly blowing in the northwest direction. The terrain of the meadow is slightly undulating; it is a part of a hill that stretches from Šenovská Street to Těšínská Street. The total elevation gain is a maximum of 40 metres per 1000 metres of distance.

Fig. 10.2. Current vegetation in Radvanice before the planting of the proposed greenery (as of 2019).

The Bartovice site (Fig. 10.3) represents the western to southwestern edge of an industrial waste landfill. Before planting greenery, there were no technical or vegetation elements in this area. The area was completely empty and barren. Near the monitored area to the west, mostly pioneer tree species can be found. The total area in Bartovice is 0.73 ha.

Fig. 10.3. Current vegetation in Bartovice before the planting of the proposed vegetation (as of 2019).

Meteorological parameters (Table 10.1) and data on air pollution concentrations were based on hourly measurements at the Ostrava - Radvanice, Nad Obcí station (ISKO 1650) operated by the Public Health Institute Ostrava. The location of the station in close proximity to both areas of interest (120 m from the Radvanice site and 1,150 m from the Bartovice site) enabled relevant assessment of the state of pollution before the project was launched. Fig. 10.4 shows the average 24-hour curve of O_3 concentrations during the growing season (April - September) and outside the growing season (January – March, October – December) in 2018. Fig. 10.5 shows the average 24-hour curve of PM_{10} concentrations during the growing season (April – September) and outside the growing season (January – March, October – December) in 2018. Fig. 10.6 shows the average daily O_3 concentrations in 2018. Fig. 10.7 shows the average daily PM_{10} concentrations in 2018.

Tab. 10.1. Average air temperature, relative humidity, global radiation, wind speed and O_3 and PM_{10} concentrations during the growing season (April – September) and outside the growing season (January – March, October – December) in 2018 at the Public Health Institute Ostrava - Radvanice, Nad Obcí station (ISKO 1650).

Period	Air temperature (°C)	Relative humidity (%)	Global radiation (W m^{-2})	Wind speed (m s^{-1})	O_3 concentrations (μg m^{-3})	PM_{10} concentrations (μg m^{-3})
outside the growing season	4.1	79.0	124.9	1.4	33.2	58.4
during the growing season	18.0	65.7	313.9	0.9	70.1	29.6

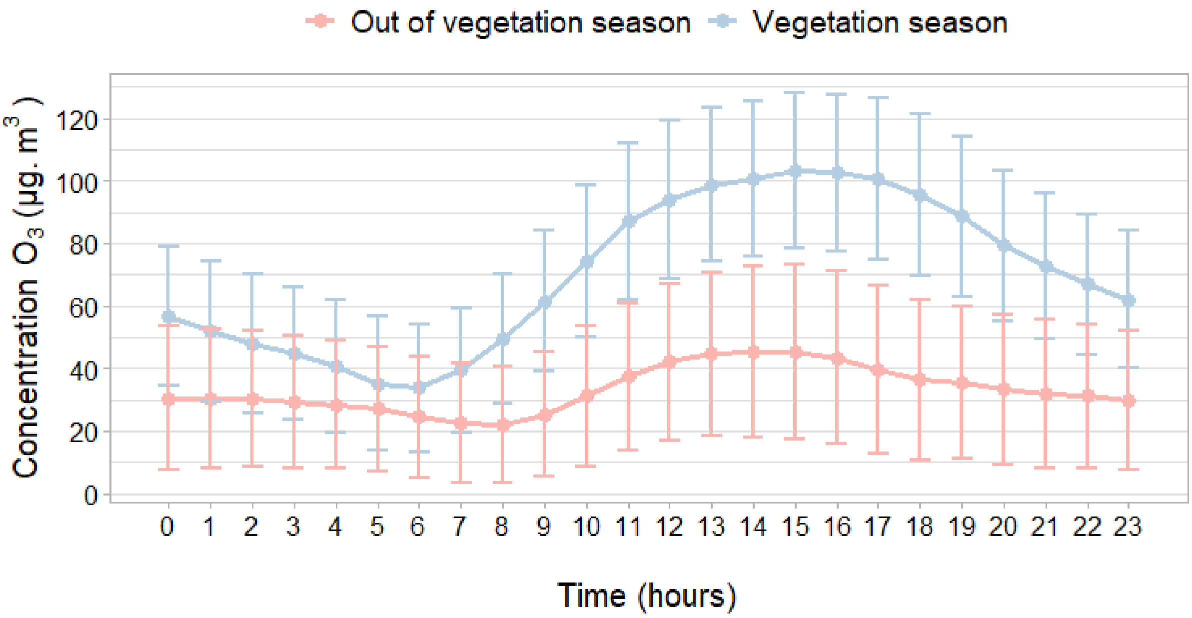


Fig. 10.4. Average 24-hour curve of O_3 concentrations during the growing season (April – September) and outside the growing season (January – March, October – December) in 2018 at the Institute of Public Health Institute Ostrava - Radvanice, Nad Obcí station (ISKO 1650). Deviations show one standard deviation from the mean.

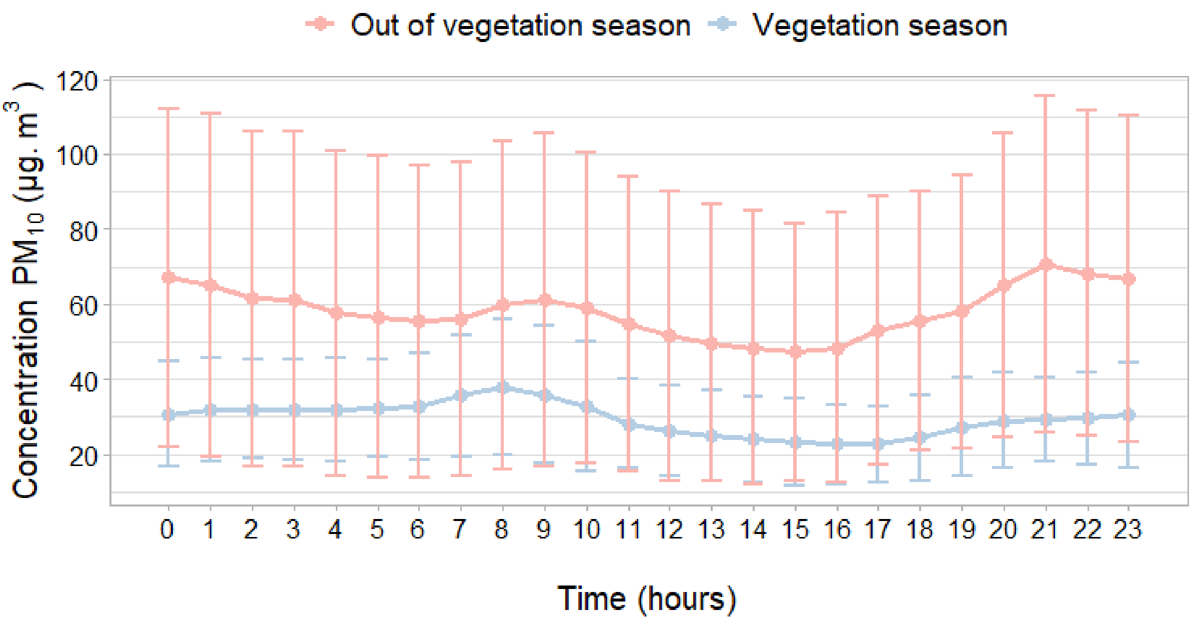


Fig. 10.5. Average 24-hour curve of PM_{10} concentrations during the growing season (April – September) and outside the growing season (January – March, October – December) in 2018 at the Public Health Institute Ostrava - Radvanice, Nad Obcí station (ISKO 1650). Deviations show on standard deviation from the mean.

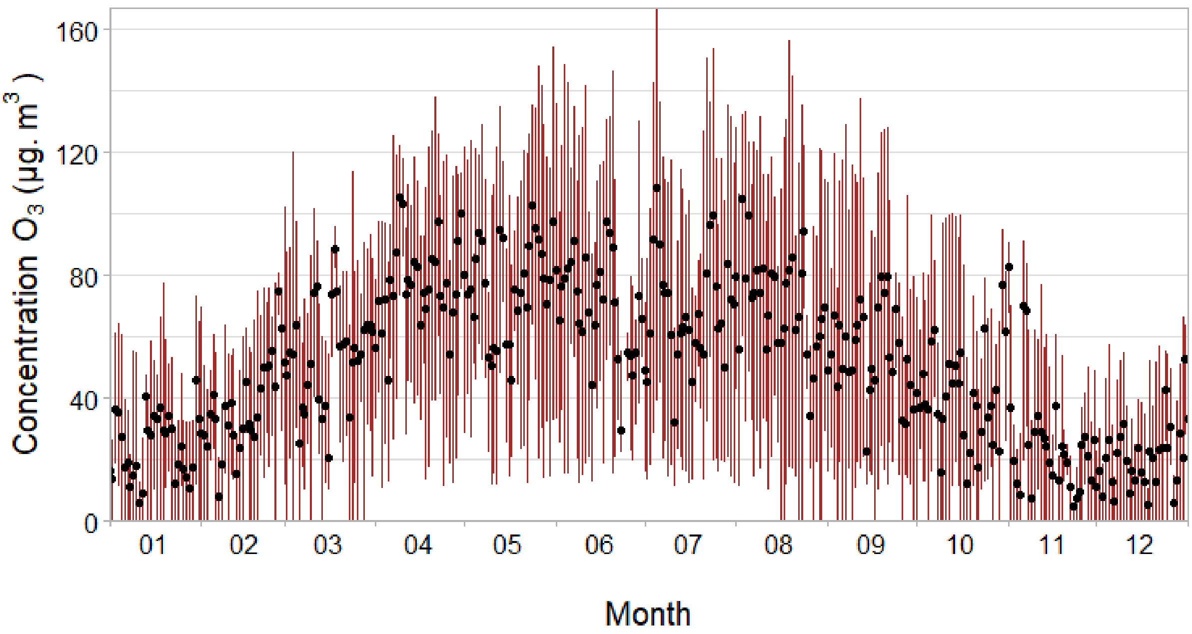


Fig. 10.6. Average daily O_3 concentrations (black dots) in 2018 at the Public Health Institute Ostrava - Radvanice, Nad Obcí station (ISKO 1650). Deviations show daily minimum and maximum values.

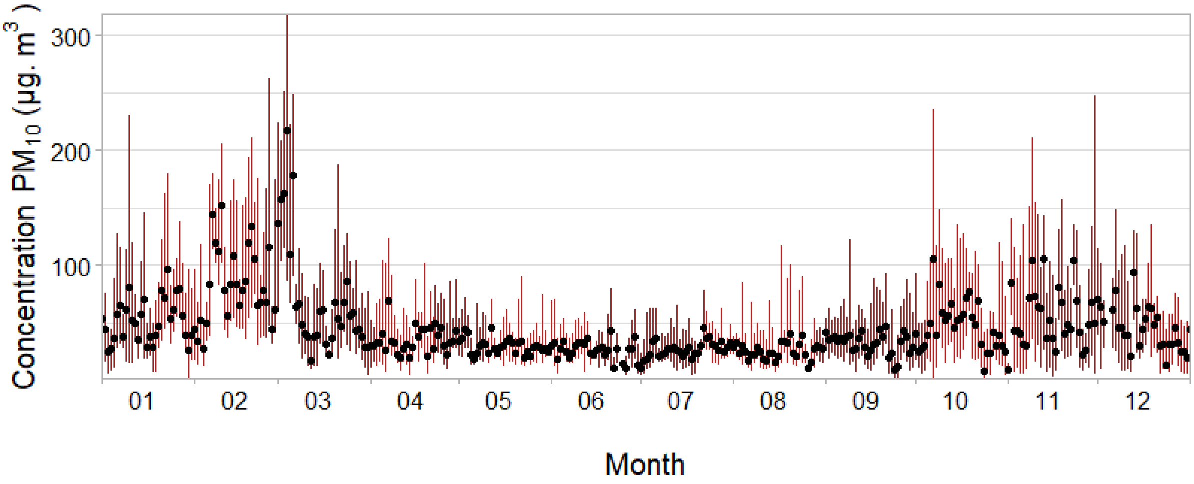


Fig. 10.7. Average daily PM_{10} concentrations (black dots) in 2018 at the Public Health Institute Ostrava - Radvanice, Nad Obcí station (ISKO 1650). Deviations show daily minimum and maximum values.

The long-term trend of PM_{10} and $PM_{2.5}$ concentrations at this station is shown in Fig. 10.8 and Fig. 10.9 (CHMI, 2019).

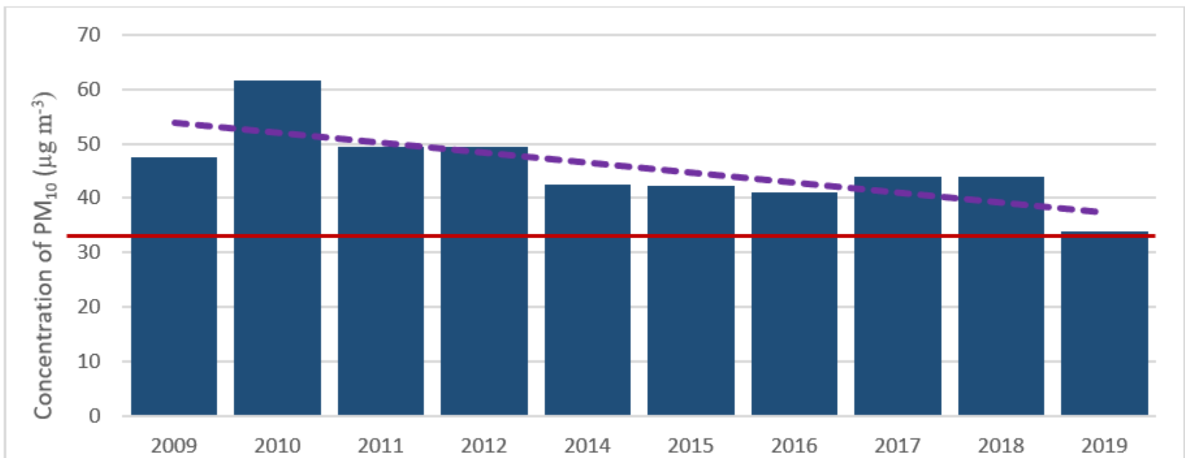


Fig. 10.8. Development trend of PM_{10} concentrations at the ISKO 1650 - Radvanice, Nad obcí station, 10 years (CHMI, 2019).

The average annual limit value of PM_{10} particles, 40 µg m^{-3}, was always exceeded in the past 10 years at this station with the exception of 2019. The reasons for the significant reduction in PM_{10} a $PM_{2.5}$ concentrations in 2019 will be the subject of research, but it is clear that very good dispersion conditions in 2019 were a significant contributing factor.

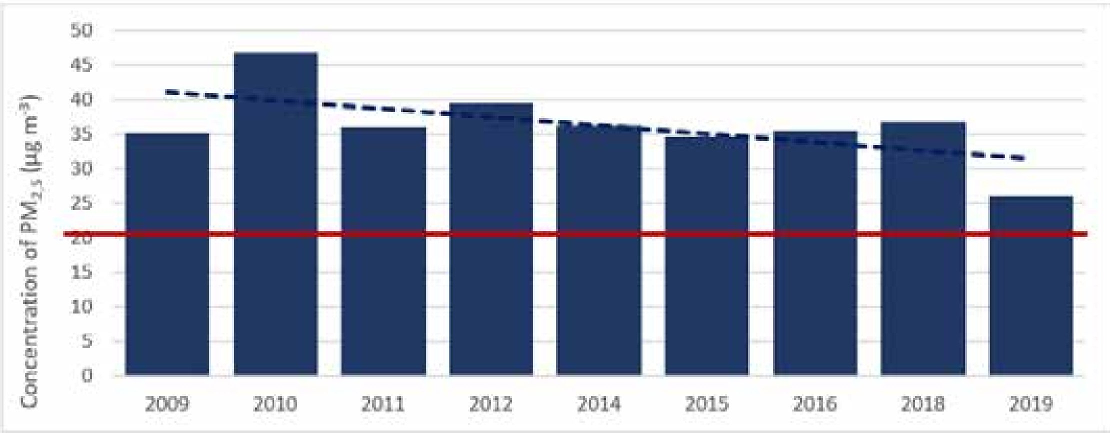


Fig. 10.9. Development trend of $PM_{2.5}$ particles at the ISKO 1650 - Radvanice, Nad obcí station, 10 years (CHMI, 2019).

The average annual limit value for $PM_{2.5}$ particles, 21,6 µg m^{-3}, was exceeded at this station every year in the last 10 years in the period from 2009 to 2019.

In the monitored area Radvanice at the ISKO 1650 Nad obcí station, the average annual concentration of NO_2 was 21.6 µg m^{-3}, whereas the highest average annual concentration of NO_2 was 31.6 µg m^{-3} in Ostrava at the ISKO 1572 Českobratrská station (CHMI, 2019).

11 AIR POLLUTION MEASUREMENT AND INFORMATION SYSTEM

11.1 SENSOR TECHNOLOGY USED

A total of 19 sensor units and one reference system were installed in the areas of interest for the purpose of monitoring the air pollution load. The sensors were installed before the greenery was planted so that the efficiency of pollutant capture by the newly planted green infrastructure could be evaluated. Continuous measurements for at least another 8 years are anticipated so that the development over time can be evaluated with the development of the greenery and connectivity of the growth.

A sensor box is installed at each measuring point - this is a device consisting of a 300 x 400 x 220 mm measuring part and a 620 x 670 mm solar panel (Fig. 11.1). The box is alternately independent of the energy source; it contains a battery and is connected to a solar panel and 220 V mains. The device is designed for installation up to a height of 3-8 m, and power supply from at least the solar panel must be ensured (there must be access to the sun).

Fig. 11.1. Photograph of typical installation at the Radvanice site.

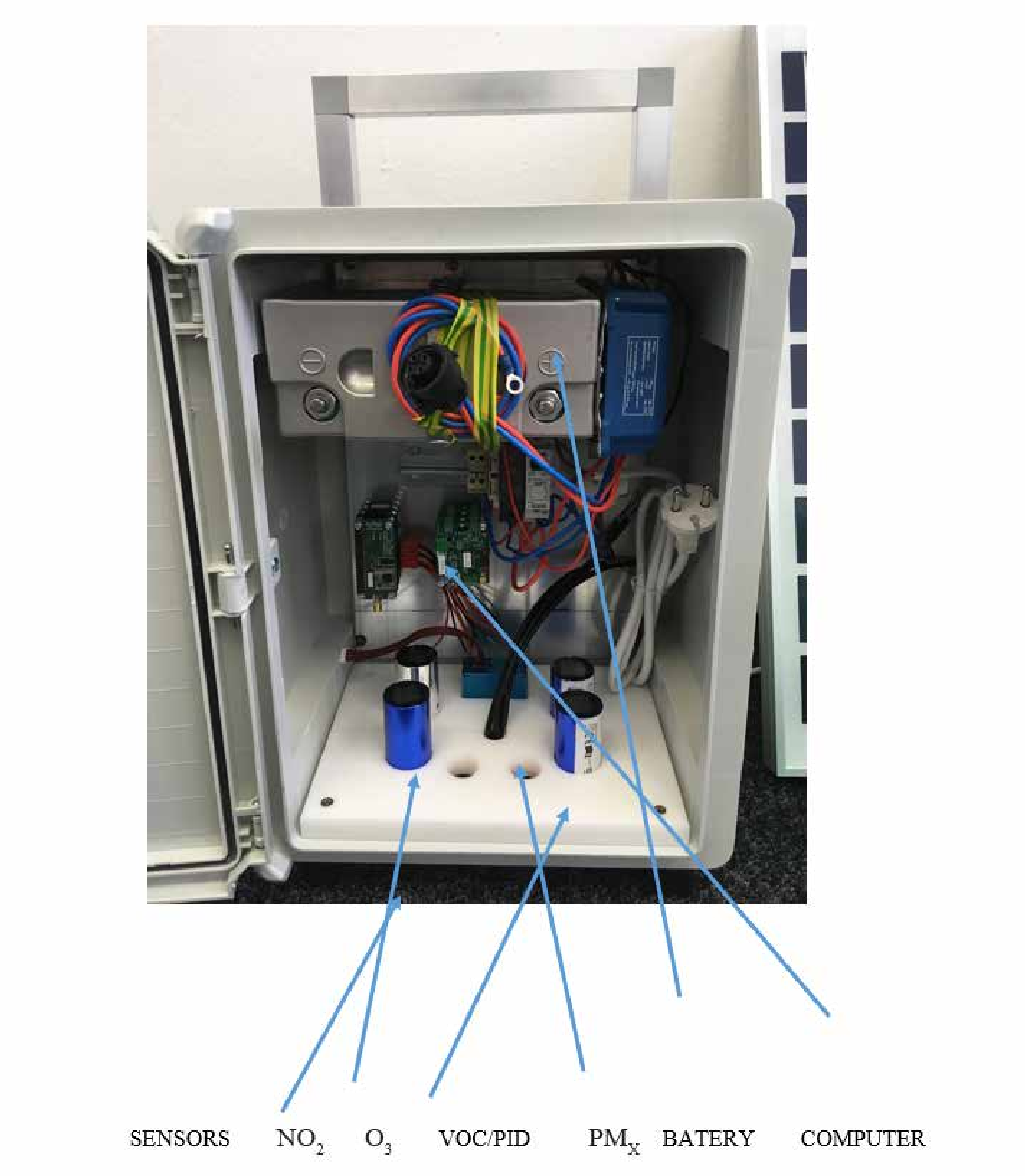


Fig. 11.2. Sensor box - sensors provide very fast measurements in a matter of minutes, which are transmitted via the LORA radio network to the database at VSB.

The sensors are placed in a box and hung on a pole at a height of about 4 metres. The distance between sensors at the Radvanice site is 10 m.

The second site in Bartovice near the fly ash storage site is equipped with sensors on the slope below the ash pond in the original greenery. New greenery will be planted near the edge of the ash pond. Here the sensors are also placed at a height of about 4 metres.

11.2 PLANTOWER SENSOR FOR MEASURING SUSPENDED PM_x PARTICLES

The Plantower sensor is an optical particle monitor that measures PM_1, $PM_{2.5}$ and PM_{10}. An internal distribution function is used to convert particles into individual classes (Plantower, 2016).

Tab. 11.1. Technical specification of PM_x sensor Plantower (Plantower, 2016).

MEASURED SUBSTANCE	PM_x
PARTICLE SIZE	od 0,3 - 20 um
NUMBER OF SIZE CLASSES	7
DETECTION LIMIT	< 1 µg/m^3
MEASURING RANGE	0 - 500 µg/m^3
SENSITIVITY	< 1 µg/m^3

The FIDAS 200 optical dust metre is used as an equivalent method to set up Plantower dust metres. The duration of the comparison of dust metres is at least 24 hours in the form of 5-minute averages. After statistical evaluation, the results were used to set a conversion or validation factor.

Fig. 11.3. Plantower sensor.

Tab. 11.2. Validation factors for the Plantower sensor, CLAIRO measurement data.

PM_{10} ($\mu g/m^3$)	Plantower	Plantower	Reference method	Validation factor
	before validation	after validation	FIDAS 200	
24-hour average	23,71	23,61	23,87	1,007
240-hour average	23,61	23,94	23,93	1,014

11.3 CAIRSENS® SENSOR FOR MEASURING NO_2/O_3

The Cairsens® O_3 / NO_2 sensor uses an electrochemical system consisting of three electrodes: working electrodes, counter electrodes and reference electrodes. They diffuse the monitored substance through a permeable membrane towards the sensitive electrode. The generated electrical signal is proportional to the gas concentration (ENVEA, 2020).

Tab. 11.3. Technical specification of the O_3/NO_2 sensor CAIRSENS
Source: https://www.envea.global/s/ambient-en/micro-sensors-a/cairsens-o3-no2/.

MEASURED SUBSTANCE	O_3/NO_2
DETECTION LIMIT	20 ppb
MEASURING RANGE	0 - 250 ppb
SENSITIVITY	1 ppb
UNCERTAINTY	< 30 %.
INTERFERENCE	Cl_2, sulfur compounds

An AC32e (ENVEA, 2020) chemiluminescence analyser of $NO/NO_2/NO_x$ was used to set up the NO_2 sensor. The duration of the comparison was 1 continuous week in 5-min. averages. The comparison was performed for 1-hour averages.

Fig. 11.4. Cairsens® O_3 / NO_2 sensor.

The Cairsens® O_3/NO_2 sensor provides an output signal in ppb; it is connected to a Rapsbery minicomputer the same way as the dust metre.

Tab. 11.4. Validation factors for the Cairsens® O_3/NO_2 sensor, CLAIRO measurement data.

Interval	**Sensor**	**Reference method**	**Sensor**	**Reference method**	**Validation factor**	**Validation factor**
	NO_2 (µg/m_3)	NO_2 (µg/m_3)	O_3 (µg/m_3)	O_3 (µg/m_3)	NO_2	O_3
24-hour average	19,12	23,90	25,72	27,15	1,250	1,056
240-hour average	15,04	18,80	19,76	20,95	1,250	1,060

11.4 DATA MANAGEMENT AND WEB PORTAL

We use the Floreon programme that VSB has been developing for over 3 years to process the data obtained by sensors. This software enables:

1. registering the sensor in the system
2. collection of primary data for the database
3. working with data, sensor validation, calibration
4. viewing data for individual substances - charts, tables
5. automatic and manual data evaluation
6. export into .csv and .txt formats

Registration is performed by the operator after communication with field workers. After the GPS coordinates are measured and the card of the measuring point is filled out (photo + description of the measuring point), this information is sent to the IIS system operator for registration. If the sensor module includes automatic GPS position detection, the sensor logs itself in.

The concentration of measured substances is transferred to the database 'Intelligent Identification System of Air Pollution Sources - IIS CZ.05.2.32/0.0/0.0/17_079/0006890' for further online processing; this database was created at VSB within the IIS project. This system can receive any transmitted data, store them in a structured database and work with them according to specified algorithms.

Data are always stored in a primarily transmitted format. In the case of calibration inspections, IIS allows the measured values to be validated by a correction factor. This is recorded in the system. Validation is generally not performed for reference methods that use the calibrated devices. PM_x determined by an equivalent method, the correction factor of which may vary slightly depending on the period and place, may be an exception. VSB regularly checks dust metres gravimetrically with its analysers.

The IIS system was developed to simplify the identification of air pollution sources on a local scale. The system is entered via the airsens.eu portal.

The control system is entered via the website at www.airsens.eu (Fig. 11.5). This website also contains information about the technology used and synergistic projects. Data obtained by the sensors may be private or public. The website interface contains both 'access for the public' and 'access for researchers' (Fig. 11.6). When 'access for the public' is selected, the user is automatically redirected to the Floreon portal, where he can view all 'free' data in the form of a chart or time-bound concentrations of each measured substance.

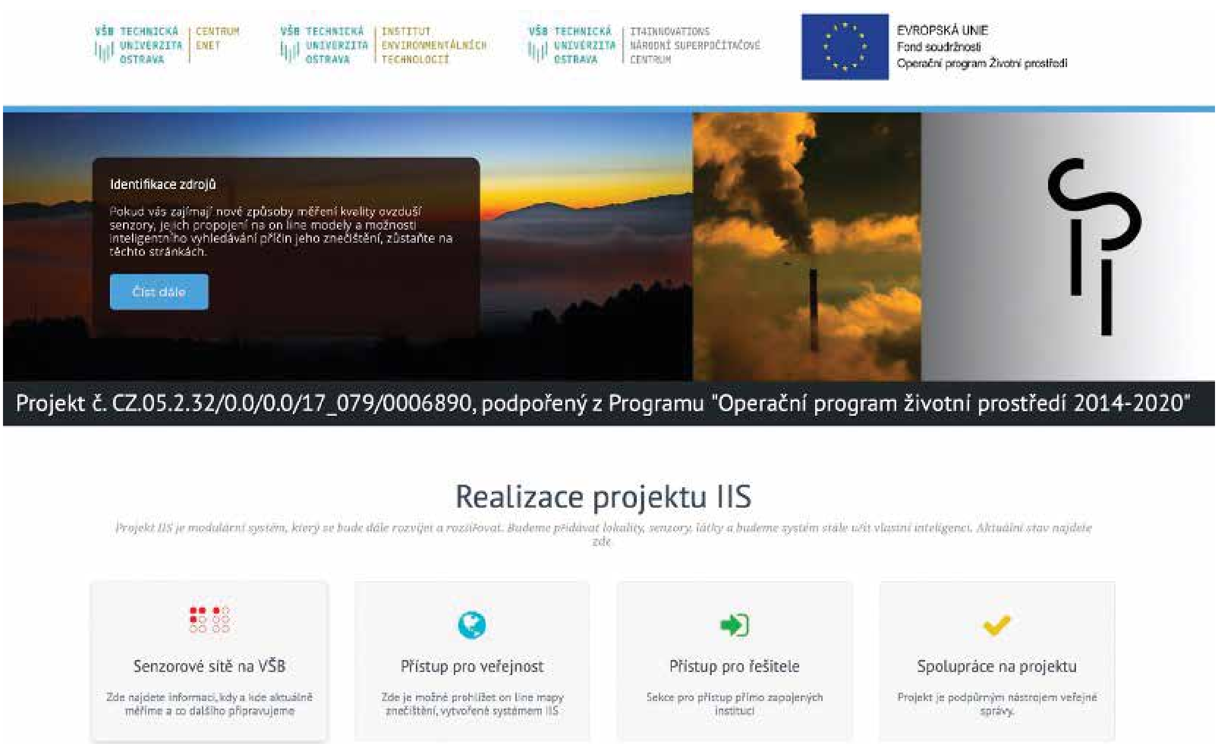


Fig. 11.5. Entry into the IIS system via the airsense.eu portal.

Fig. 11.6. Access to free data of a public and registered user.

The reason the data is divided into public and private data is the existence of measurements performed in the private sector, which cannot be freely published. This can be data of private individuals or private companies, or project research.

The system allows choosing substances, sites and periods, and it performs basic statistical evaluations. It checks the valid measurements, calculates the averages and finds the maxima of the measured concentrations. It displays the measured concentrations in a chart. These data are used to check data consistency, or for comparison with other measurements.

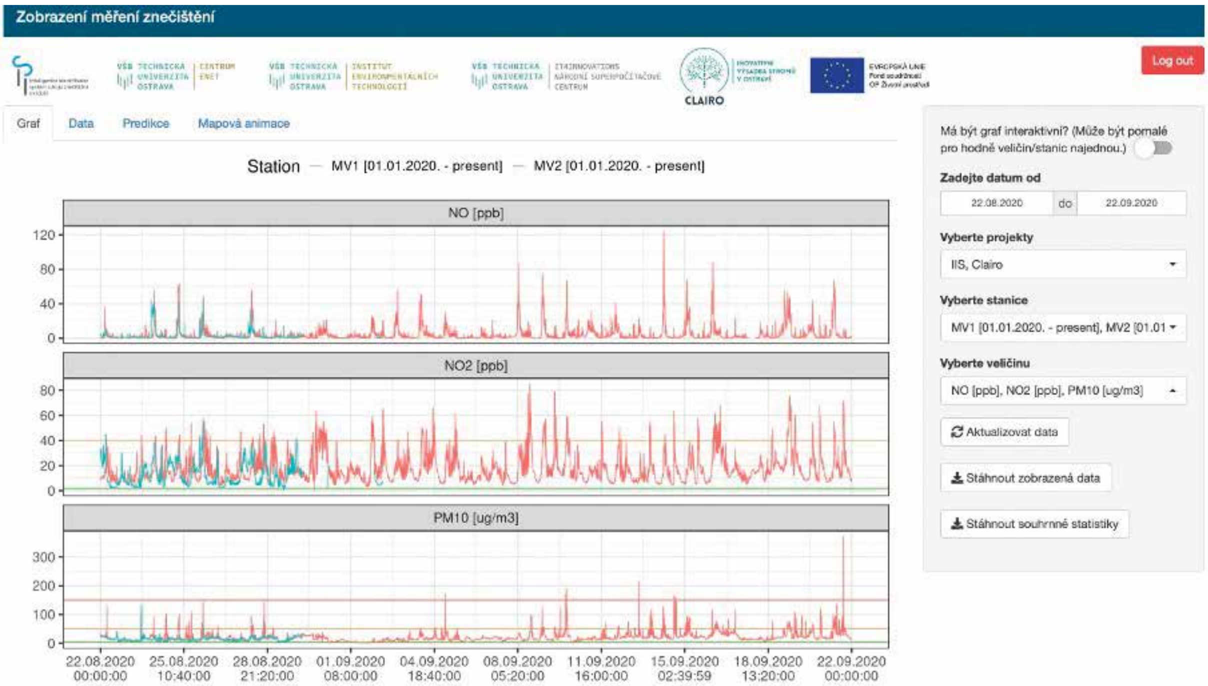


Fig. 11.7. Depiction of pollution measurement.

In the right part of the menu we can select the monitored period (day, week), the sensor station by name (STC, STP, ST), the measured substance and enter update. There is also a 'Select projects' tab, where we choose synergetic projects, such as IIS or CLAIRO air pollution measurements. If we don't know which project the sensor belongs to, we choose 'all projects'. Once updated, a chart of selected items will be displayed, see Fig. 11.8.

	Stanice	Veličina	Vzorkování [min]	Všechna pozorování	Validní pozorování	Minimum	Ar. průměr	Geom. průměr	Maximum
1	MV1 [01.01.2020. - present]	NO [ppb]	5	8929	8758	0	4.5	0	124.2
2	MV1 [01.01.2020. - present]	NO2 [ppb]	5	8929	8926	0	17.7	0	85.2
3	MV1 [01.01.2020. - present]	PM10 [ug/m3]	5	8929	8926	1	21.3	16.8	372.3
4	MV2 [01.01.2020. - present]	NO [ppb]	5	8929	2531	0.2	2.8	1.7	45.2
5	MV2 [01.01.2020. - present]	NO2 [ppb]	5	8929	2530	0.4	12.7	9.7	57.8
6	MV2 [01.01.2020. - present]	PM10 [ug/m3]	5	8929	2409	3.3	15.5	14.1	132.9

Showing 1 to 6 of 6 entries   Previous 1 Next

Fig. 11.8. Basic statistical data from measurements.

All statistical characteristics for the selected period are displayed in the same way. You can find the places with the highest average concentration, with the highest maxima, places that exceed the limit most frequently, etc. The result of this process is an evaluation of when and where the set rules are violated (limit, regulatory limit, monitoring limit, rate of increase in concentrations, correlation with other attributes, etc.).

These tools do not need to be used for CLAIRO data in cities, because the aim here is not to identify.

Thanks to short-term concentrations, we can find the time and place of 'unusual or unwanted' air pollution concentrations. The IIS system uses specified rules to indicate where and when the set concentration level was exceeded (increased). The system allows automatic animation of measured concentrations.

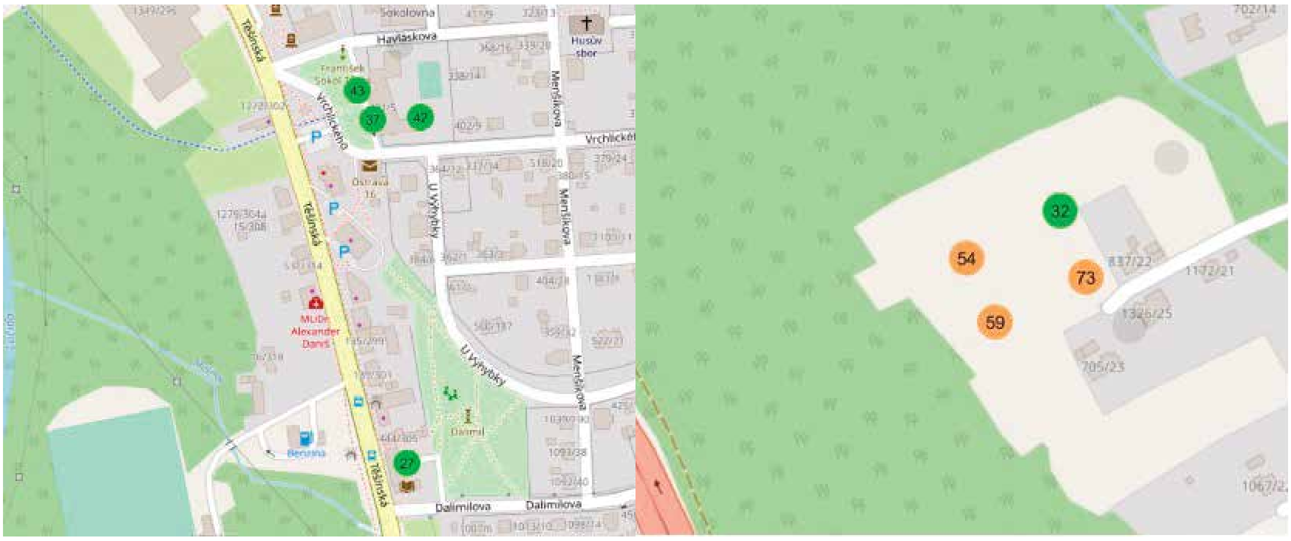


Fig. 11.9. IIS map section – depiction of measured concentrations (PM_{10}).

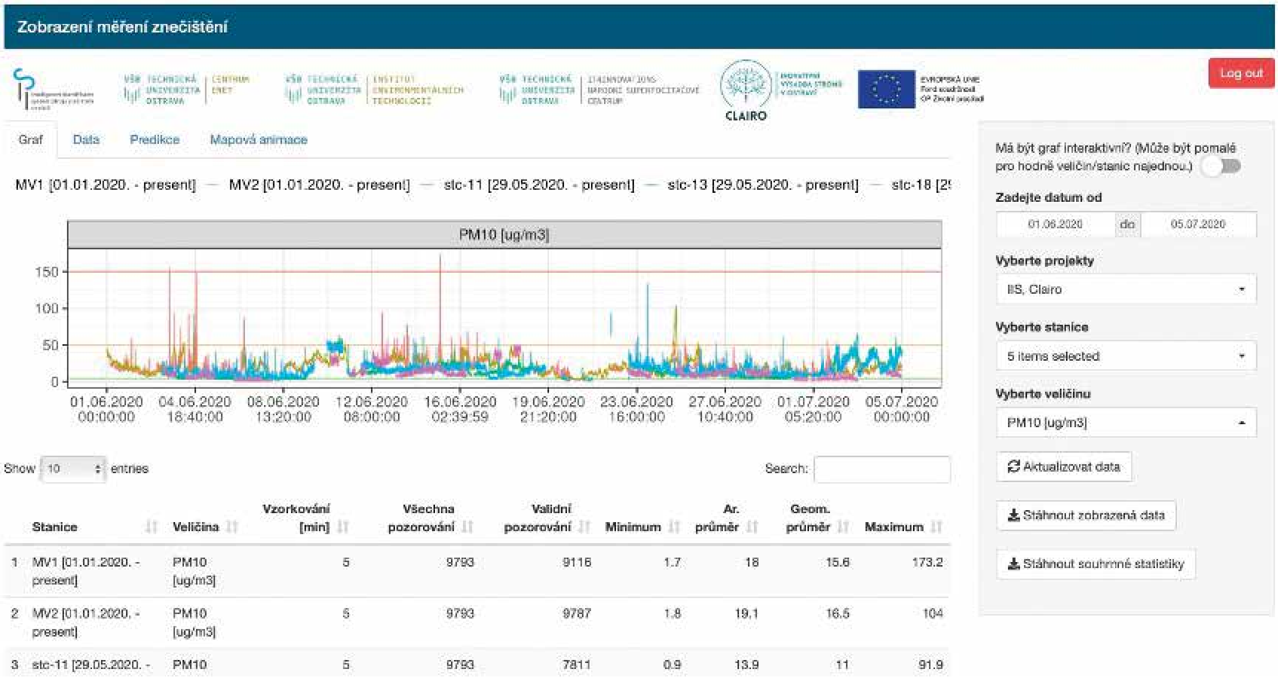


Fig. 11.10. Depiction of measured data in the control software.

The chart can be used to check one sensor unit (time course) or to check the 'comparison' of several units. The table below the chart always shows the basic statistics, e.g. the number of 'planned' measurements in the selected interval and the number of valid measurements. This gives us basic information on how the sensor works. We also see the sample mean, the average concentration, the minimum and maximum for a given interval.

The displayed data can be downloaded in *.csv format and worked with further, e.g. in MS Excel.

The data are transferred to the database according to the possibilities of the transmission network; the basic assumption is every 5 minutes for field measurements (GPRS, LORA) and immediately in the case of technical measurements inside buildings (WiFi).

The web interface enables the 'calibration or validation' of all sensors. For this purpose, you need to switch to the MANAGEMENT tab. Now you can choose a project, sensor and database type.

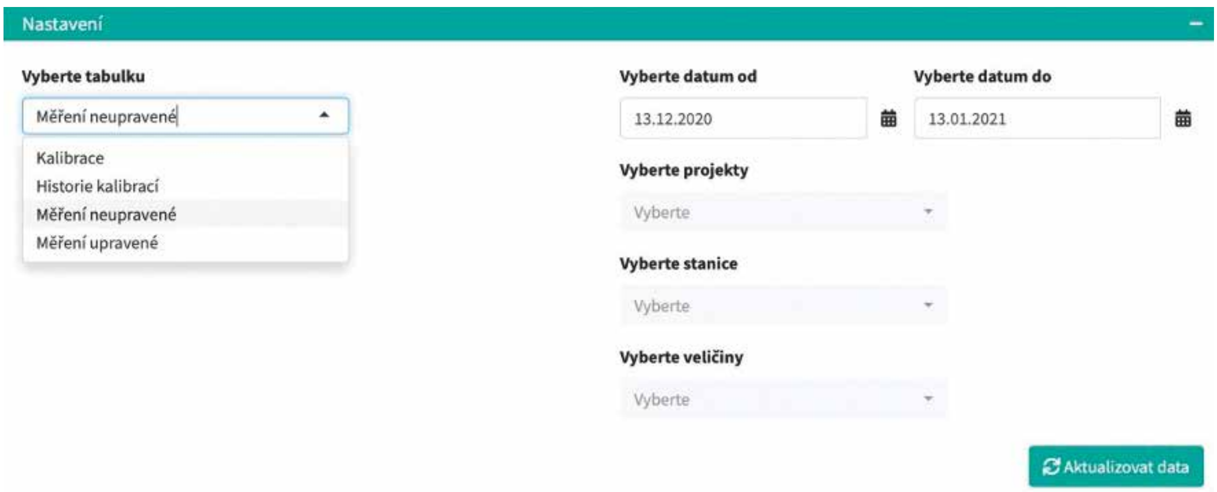
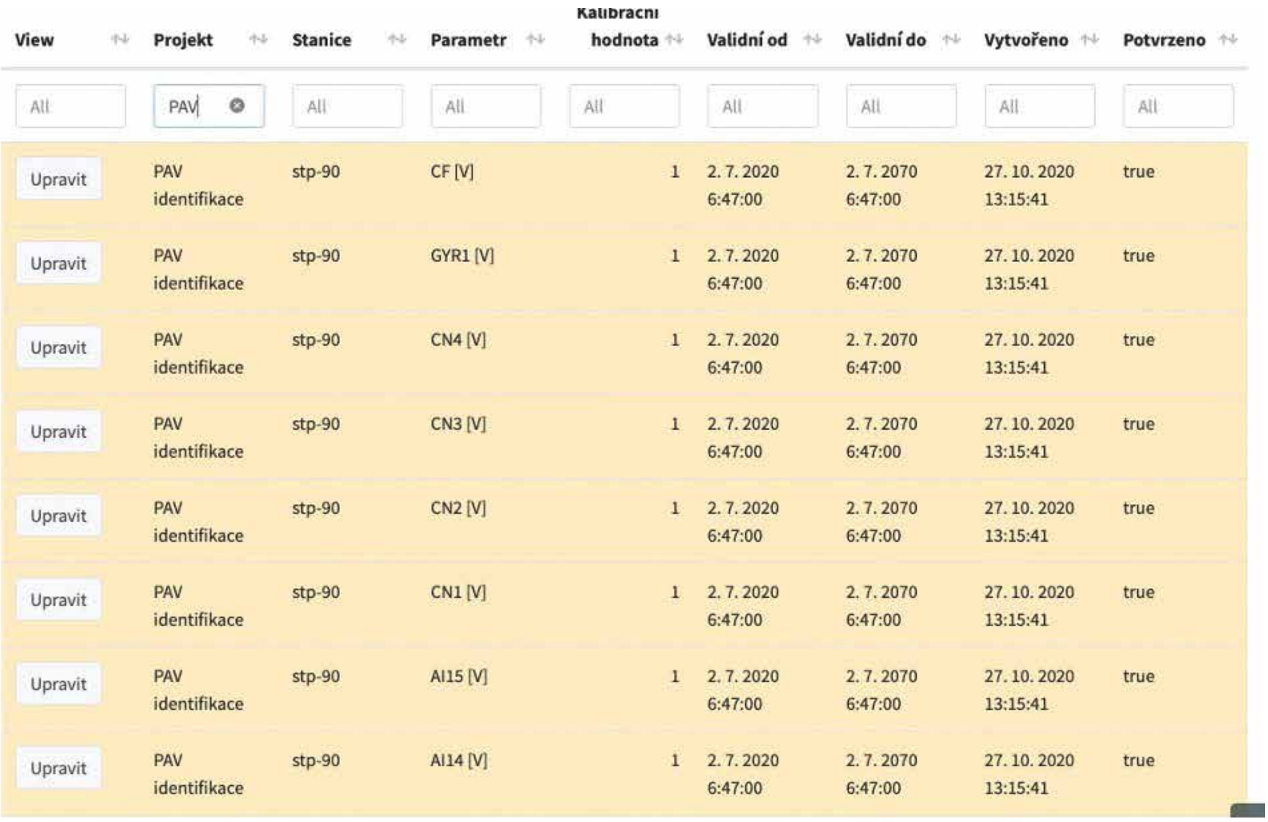


Fig. 11.11. Settings.

UNADJUSTED MEASUREMENTS are native measured values, i.e. the original signal. ADJUSTED MEASUREMENTS are values that are recalculated using calibration factors. In the CALIBRATION tab you can set the validity period of the factor, sensor and substance that you want to calibrate. Each factor is saved in the CALIBRATION HISTORY.



View	Projekt	Stanice	Parametr	Kalibrační hodnota	Validní od	Validní do	Vytvořeno	Potvrzeno
All	PAV	All	All	All	All	All	All	All
Upravit	PAV identifikace	stp-90	CF [V]	1	2. 7. 2020 6:47:00	2. 7. 2070 6:47:00	27. 10. 2020 13:15:41	true
Upravit	PAV identifikace	stp-90	GYR1 [V]	1	2. 7. 2020 6:47:00	2. 7. 2070 6:47:00	27. 10. 2020 13:15:41	true
Upravit	PAV identifikace	stp-90	CN4 [V]	1	2. 7. 2020 6:47:00	2. 7. 2070 6:47:00	27. 10. 2020 13:15:41	true
Upravit	PAV identifikace	stp-90	CN3 [V]	1	2. 7. 2020 6:47:00	2. 7. 2070 6:47:00	27. 10. 2020 13:15:41	true
Upravit	PAV identifikace	stp-90	CN2 [V]	1	2. 7. 2020 6:47:00	2. 7. 2070 6:47:00	27. 10. 2020 13:15:41	true
Upravit	PAV identifikace	stp-90	CN1 [V]	1	2. 7. 2020 6:47:00	2. 7. 2070 6:47:00	27. 10. 2020 13:15:41	true
Upravit	PAV identifikace	stp-90	AI15 [V]	1	2. 7. 2020 6:47:00	2. 7. 2070 6:47:00	27. 10. 2020 13:15:41	true
Upravit	PAV identifikace	stp-90	AI14 [V]	1	2. 7. 2020 6:47:00	2. 7. 2070 6:47:00	27. 10. 2020 13:15:41	true

Fig. 11.12. 'Calibration' tab.

All values are natively set to 1.00. When you click on the ADJUST button, a simple menu will appear.

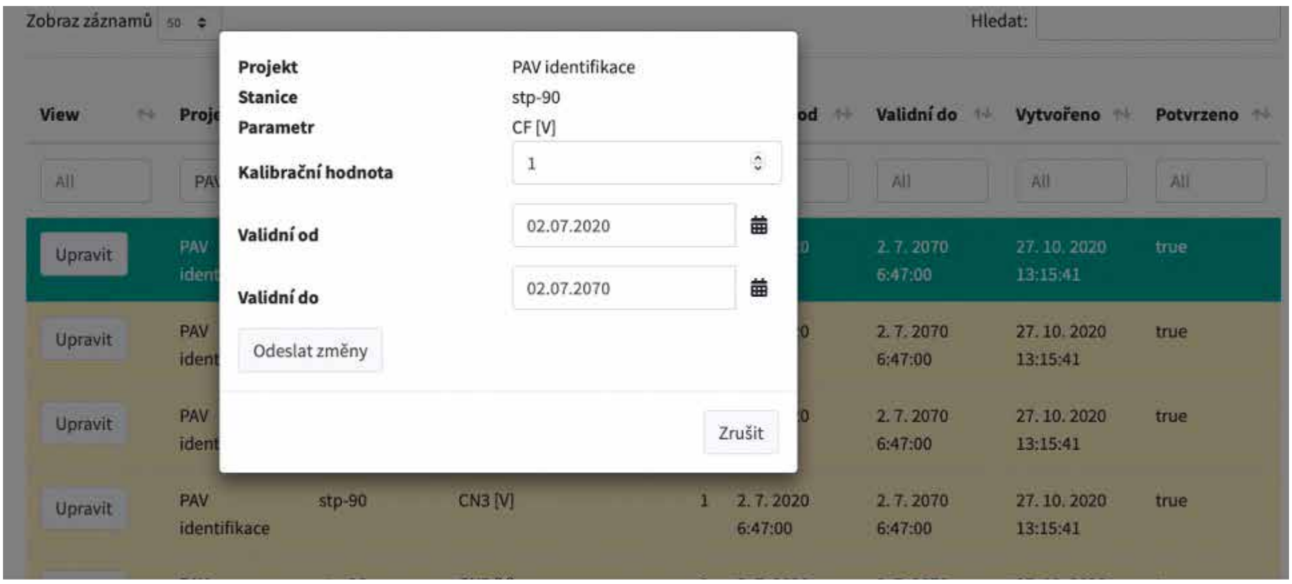


Fig. 11.13. Setting the calibration value.

Here you have to change the calibration value and set the validity period. After you set the calibration factor, the original database for the selected period will be recalculated for the given sensor and substance. In the ADJUSTMENT MEASUREMENTS tab you will find the recalculated values.

Even after calibration, the values can be manually invalidated with the INVALIDATE button. Invalidated values are not included in the averages and statistics.

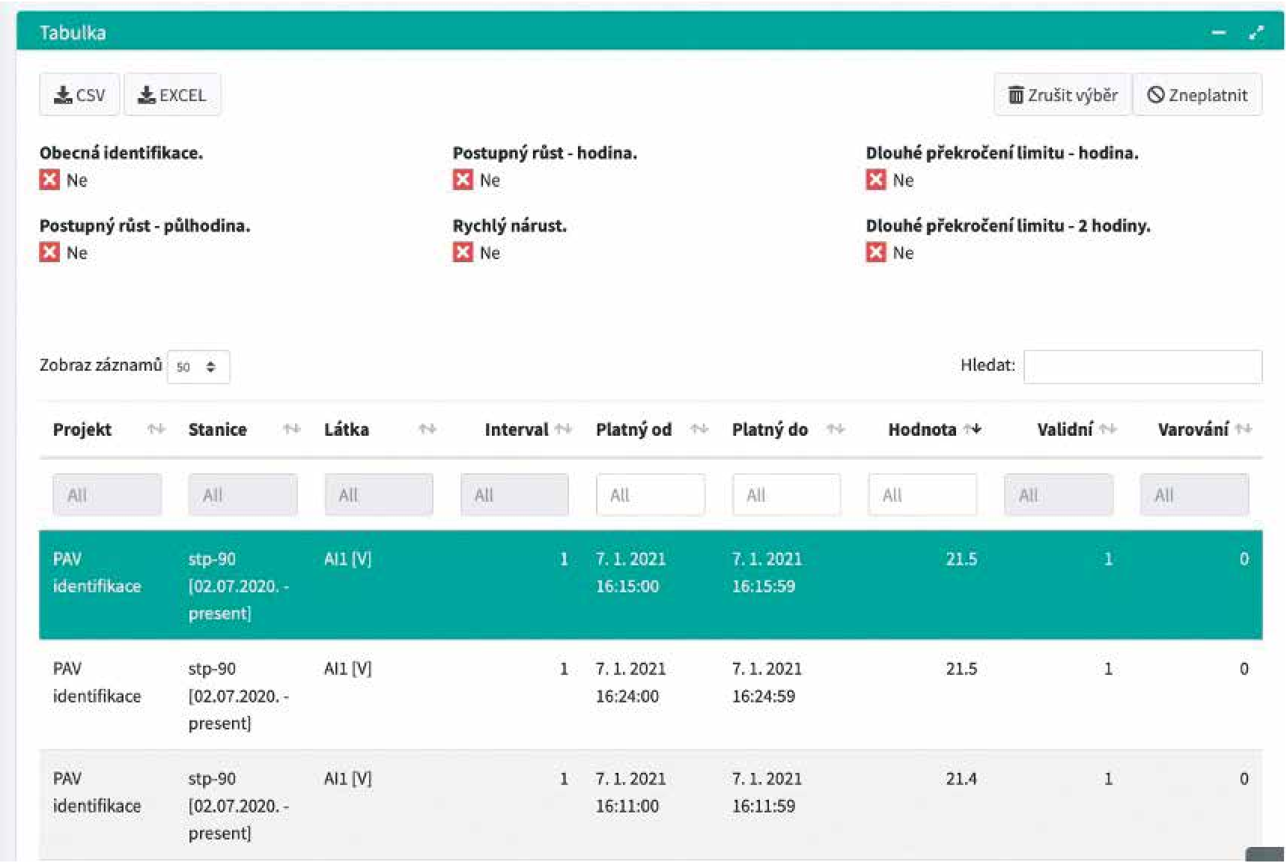


Fig. 11.14. Table - download option.

For further work, the selected data can be downloaded in *.csv or *.xls format. The calibration factor must contain all detailed calculations. If the calculation is complex, it must be done in exported data.

The history of calibrations used can be monitored in the CALIBRATION HISTORY tab.

Thanks to the above, the professional part of the Airsens portal enables measuring any substances, not only in the air, and these measured concentrations can be checked in terms of accuracy and evaluated in terms of the information they provide. The overall size of the database is evidenced by the fact that in 20 months of measurements in the CLAIRO project, the database has 28 million rows. This is a why a high-quality, robust tool is necessary as described above.

11.5 EXAMPLE OF REAL OUTPUT

An annual evaluation of PM_{10} and NO_2 at the Radvanice site is given as an example. The aim of the evaluation is to describe the site with the 11 installed sensors.

PM_{10} (µg/m³)	MEAN	MEDIAN	MAXIMUM
S1	28,09	22,45	233,09
S2	27,72	21,54	210,69
S3	31,84	25,09	236,38
S4	23,87	19,98	165,32
S5	27,84	20,46	234,66
S6	30,04	21,12	282,82
S7	33,84	26,11	222,28
S8	27,87	20,49	223,86
S9	30,57	25,11	235,86
S10	27,72	21,55	214,19
S11	32,76	26,72	212,88
MEAN		**22,78**	**224,74**

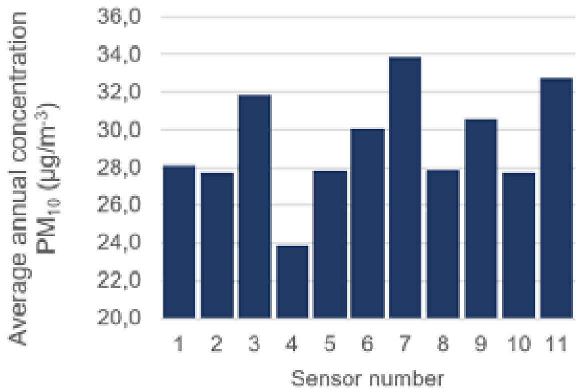


Fig. 11.15. Mean annual PM_{10} concentrations at the Radvanice site, 1/9/2019 – 31/8/2020, table (on the left) and chart (on the right).

NO_2 (µg/m³)	PRŮMĚR	MEDIAN	MAXIMUM
S1	22,8	15,3	264,0
S2	22,5	14,6	211,9
S3	21,6	15,0	269,2
S4	25,2	16,3	270,8
S5	25,5	18,8	190,1
S6	24,5	17,9	202,6
S7	23,1	16,5	199,4
S8	23,6	15,4	253,3
S9	24,3	16,0	233,2
S10	23,2	15,7	217,3
S11	22,3	15,7	173,1
MEAN		**16,1**	**225,9**

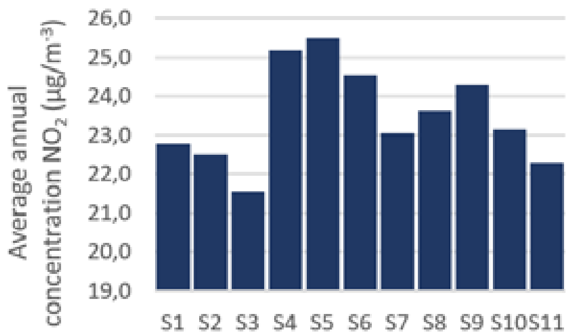


Fig. 11.16. Mean annual NO_2 concentrations at the Radvanice site, 1/9/2019 – 31/8/2020, table (on the left) and chart (on the right).

The examples describe simple data in the tables, which are based on a year of measurement at the Radvanice site.

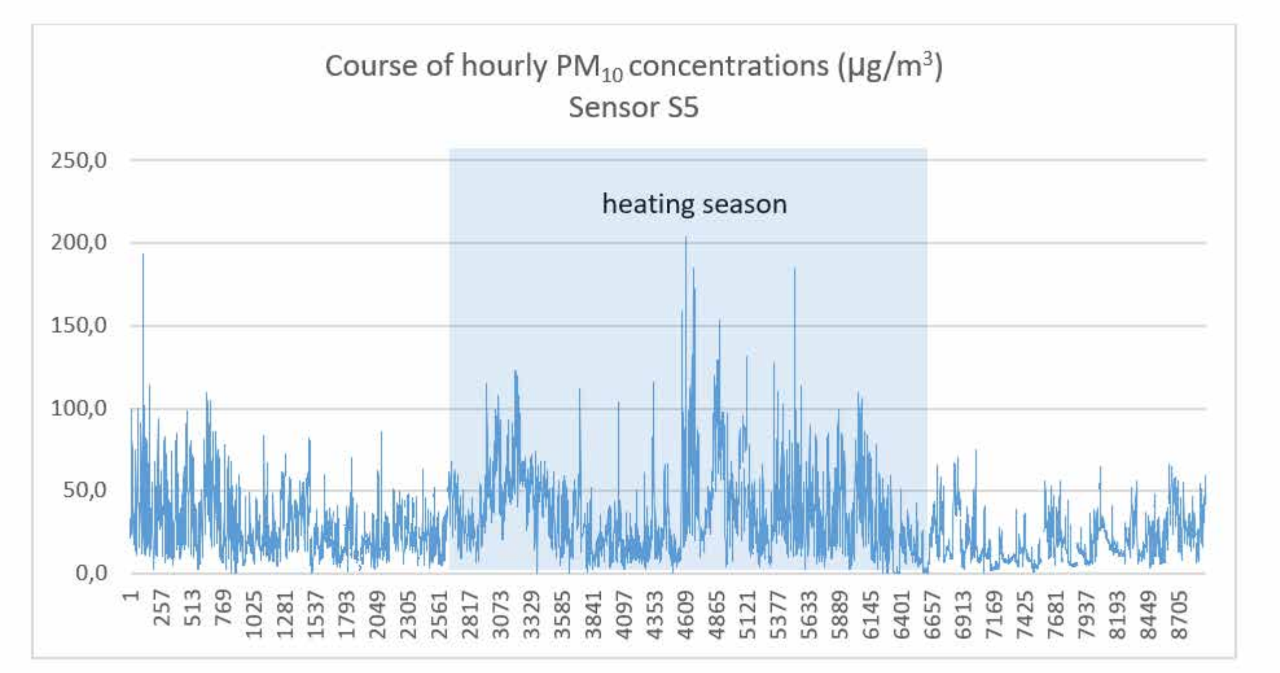


Fig. 11.17. Chart of annual hourly PM_{10} concentrations at the site.

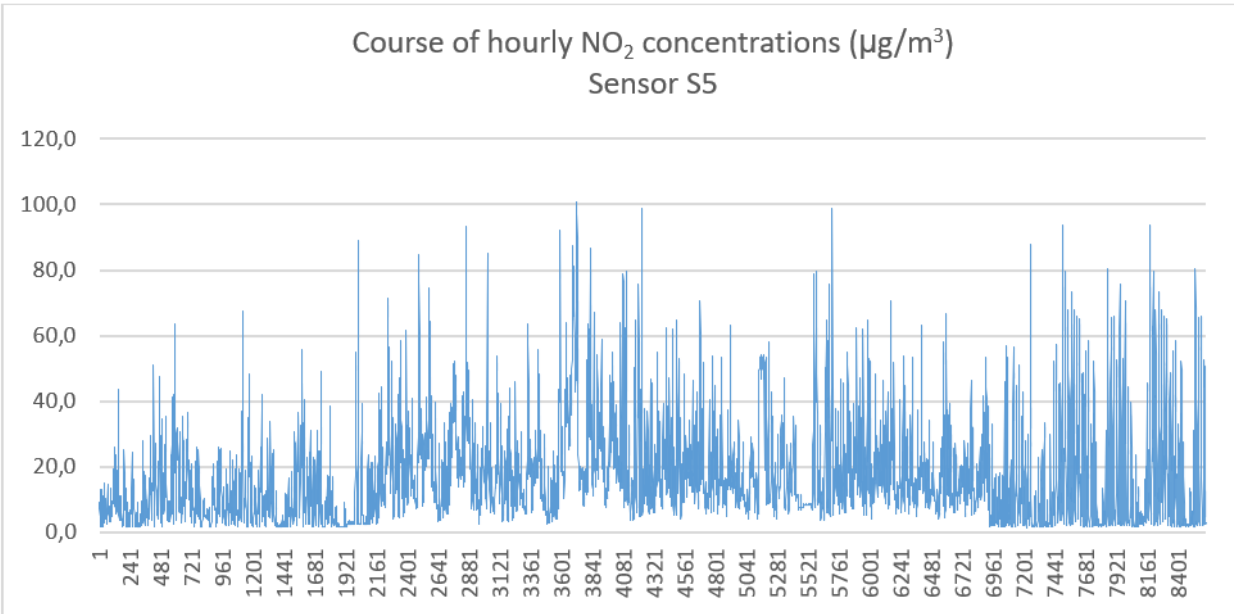


Fig. 11.18. Chart of annual hourly NO_2 concentrations at the site.

The very extensive database of measured concentrations makes it possible to monitor long-term changes in the concentrations of measured substances, and the results are very robust thanks to the large number of sensors at the site.

The measurements from the sensors are very dynamic and they help us understand the immediate changes in concentrations associated with various processes that take place at the site; however, it is important to realize that the use of sensors to assess air pollution limits is not proper and it has no support in legislation. Nevertheless, the sensors can use the concentration difference method to perfectly describe what is happening in the area, namely to discover sources of high emissions, etc. Sensors are an excellent and affordable solution for comprehensive site descriptions and finding the causes of pollution.

12 GREENERY PLANTING DESIGN

The design of the structure of the plant community focused on habitat-appropriate tree species in combinations with similar ecological requirements, including layering, the provision of ecological cover and streamlining air filtration. Ecological cover and maximization of pollutant capture will be ensured through the cultivation of woody plants in a closed canopy.

Plant species were selected on the basis of available scientific materials on the planting of green infrastructure in residential areas. The structure of the planted greenery was designed to monitor the function of air filtration and resistance in industrially stressed areas. Fulfilment of the objectives of the experiment consisted in the design of a continuously connected differentiated tree community. The proposal for the cultivation of a continuous tree community was adopted according to forestry criteria. Criteria of habitat differentiation, tree mixtures and planting density were used.

Species with increased resistance to air pollution were preferred. The resistance of trees was simplified to classify the degree of tolerance to the deposition of sulfur and nitrogen, tropospheric ozone and solid dust particles. In industrial areas with increased concentrations of tropospheric ozone, it is necessary to pay attention to the sensitivity of the proposed greenery to this pollution when designing the composition of green infrastructure.

The parameters of the species composition were determined with regard to the ecological relationships between individual species and their requirements for the given habitat, which was characterised by soil analysis. The individual species combinations are compatible in terms of growth and demands - the individual layers do not compete in terms of growth and aggressiveness, and the undergrowth tolerates shading. The arrangement of species relative to each other is not important, but for a more regular distribution, they will be planted according to an exact planting scheme. The distribution of taller tree species compared to undergrowth trees and their regular distribution in the area ensures good efficiency of capturing exhalations.

The process of designing the structure of greenery includes the criteria of planting material, allelopathy and replenishment of cultures. The following principles were taken into account in the selection:

- Planting material was planted in the form characterised by territorially relevant standards. Plants with a root ball are used for planting.

- Native, uncultivated plant forms were preferred, with the exception of an experiment comparing uncultivated and cultivated plant forms. Native plant species were exclusively selected from geographically native uncultivated populations to preserve the gene pool. Cultivated forms were only allowed when uncultivated forms of the proposed non-native species were unavailable.

- Plants grown in habitat-appropriate conditions were preferred. The transfer of reproductive material was only permitted in accordance with international or national law.

- Tree layers and a shrub layer. Tree layers are divided into upper canopy layer and understory layer.

- Species with increased resistance to air pollution were preferred. The resistance of trees was simplified to classify the degree of tolerance to the deposition of sulfur and nitrogen, tropospheric ozone and solid dust particles.

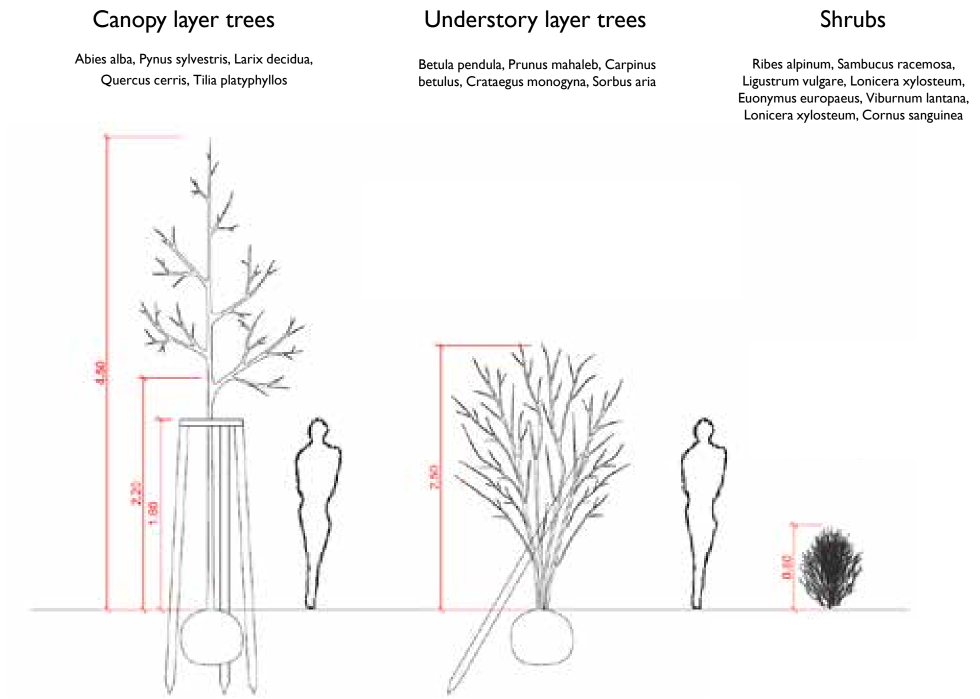


Fig. 12.1. Height and species representation of vegetation elements in the proposed greenery - the proposed trees are divided into two vertical vegetation layers - the canopy layer with a canopy height of 2.2 m, and the understory layer of multi-stemmed trees branched from the ground.

The composition of the proposed greenery consisted in the spatial differentiation of the multi-layer tree and shrub communities. The following criteria were used:

1) Two tree layers and a shrub layer in order to maximize the canopy density in places with the highest pollution. Tree layers divided into a canopy layer and understory layer.

2) Trees up to 4 m in height preferred for the canopy layer, and up to 2.5 m in height for the understory layer.

3) Minimum spacing between trees taking into account their space requirements in mature state. The planting was planned in a uniformly regular network (ideally hexagonal).

The greenery planting plan at the Radvanice site was situated in the preserved habitat conditions typical for the wider region of the Ostrava Basin, where the proposed vegetation consists of geographically native species.

In contrast, the proposed planting at the Bartovice site was on soils heavily anthropogenically affected by waste materials, where the proposed vegetation is based on a comparison of a combination of non-native resistant species and pioneer species.

The plan for planting greenery at the Radvanice site is shown in Fig. 12.2. The trees were placed in rows 6 m apart. The same spacing between trees was kept in each row. In places with a stagnosols soil type, mulched shrub plantings were proposed over the entire area in rows 1.5 m apart. The following species were used: *Quercus petraea, Acer pseudoplatanus, Tilia platyphyllos, Populus nigra, Salix daphnoides, Ulmus laevis* (upper canopy layer), *Acer campestre, Crataegus monogyna, Prunus padus, Lonicera xylosteum, Prunus avium* (understory layer), *Viburnum opulus, Alnus viridis, Frangula alnus, Rosa majalis, Salix purpurea* (shrubs).

Fig. 12.2. Greenery planting plan at the Radvanice site.

The plan for planting greenery at the Bartovice site is shown in Fig. 12.3. The tree layout was designed in rows that are 6 m apart in the central part of the monitored area. The distance between individual rows is reduced to 4.5 m at the edges. In each row, the trees are 6 m apart. A total of 203 trees were proposed. The following species were used: *Pinus sylvestris, Larix decidua, Quercus cerris, Tilia platyphyllos* (upper canopy layer), *Betula pendula, Malus sylvestris, Carpinus betulus, Crataegus monogyna, Sorbus torminalis* (understory layer), *Ribes alpinum, Sambucus racemosa, Ligustrum vulgare, Lonicera xylosteum* (shrubs).

Fig. 12.3. Plan for planting greenery at the Bartovice site.

The main benefit of the chosen composition is the adequate drought resistance of the species combination and their efficiency in capturing dust particles throughout the year due to the addition of coniferous trees. The proposed solution is applicable to other areas that have similar soil properties.

13 TREATMENT OF GREENERY

At the site of the proposed green infrastructure, several types of fertilisers are applied and their impact on the quality of the greenery is monitored, which ultimately reflects on the ability to capture pollutants from the air.

The soil is specifically treated with three types of fertilisers: (1) a common commercial inorganic fertiliser, (2) a commercial biostimulant with a high content of amino acids, anti-stress substances and seaweed extract limiting potential negative environmental influences (TS entinel, TS VIN), and (3) an innovative smart fertiliser with the active substance cytokinin derivative RR-D.

All other standard crop treatments (watering, weeding, etc.) are the same for all three variants - at the same time in the same amount, etc., so that the effect of the applied fertilisers is distorted as little as possible by other factors.

The main prerequisite for the application of innovative treatment is the improvement of the basic physiological parameters of the new greenery. These are monitored by a number of highly sensitive and unique methods (gasometry, detection of selected fluorescence parameters, content of photosynthetic pigments, measurement of endogenous phytohormone levels using a combination of ultra-efficient liquid chromatography and tandem mass spectrometry) in order to assess the impact of the innovative treatment on the physiological condition of new plantings and existing vegetation at selected sites and, if necessary, to propose further optimisation of this treatment.

The combination of phytohormones and biostimulants proposed for this project is a unique result of up to 20 years of research conducted in the Laboratory of Growth Regulators, Faculty of Science, Palacký University, and the Institute of Experimental Botany of the Czech Academy of Sciences; it is the subject of several international patents (Doležal et al., 2007; et al., 2009) licensed to Czech and foreign companies operating in the field of foliar fertilisers. The treatment product contains an optimal mixture of biostimulants with a high content of amino acids, anti-stress substances and seaweed extract, limiting potential negative effects of the external environment, especially during drought or significant temperature fluctuations, and tested on forest cultures. This preparation will be used as a basis for the application of our active substance, a patented cytokinin derivative. There are 2 different types of soil conditions at both sites. This means that each of the sites will be divided into six sub-sections (3 sections for each soil type) so that the individual sub-sections can be treated with three types of fertilisers (classic fertiliser A, commercial fertiliser based on modern biostimulants B, and innovative fertiliser C). Variant A will be treated on the same dates as the remaining variants, but only with fertiliser containing a common commercial inorganic fertiliser chosen by the planting company based on its experience. Option B, i.e. treatment with a commercial biostimulant, will take place twice a year (June and August-September in the first year, April and August-September in the following years). The product TS Sentinel (https://www.trisol. farm/pripravky_profi/sentinel.html), TS VIN (https://www.trisol.farm/pripravky_profi/vin.html) or a similar product from another company containing an optimal combination of biostimulants with a high content of amino acids, anti-stress substances and seaweed extract, limiting potential negative effects of the external environment, especially during drought or significant temperature fluctuations, and tested on forest cultures, was chosen for the CLAIRO project. The dose of 2.5 ml/ plant must be diluted with about 2L of water before application. To begin with, we suggest applying TS HG Plant or a similar product containing humic acids, anti-stress substances and seaweed extracts once (https: // www.trisol. farm/pipravky_profi/hg-plant.html) in a dose of 2 g per plant, ideally for all three variants, or at least for variants B and C. Product B will be used as a base for the application of our active substance, cytokinin derivative RR-D (at a concentration of 10-5 mol / L), i.e. variant C. The products will be applied on the same dates as variant B. Both variants (B and C) will be completely prepared by Palacký University in Olomouc and delivered to the implementing company at least one week before each application. All other standard crop treatments (watering, weeding, etc.) should be the same for all three variants - on the same dates, in the same amounts, etc., and they should be carried out regularly by the planting company to ensure evaluation and comparison of individual treatment variants. This is far from the first application; however, their use in the CLAIRO project is unique in some respects, especially the levels and combinations of different types of abiotic stress at selected sites. The main prerequisite for the application of innovative treatment is the improvement of the basic physiological parameters of the new greenery. The prognosis assumes that trees and shrubs in better "health" will better photosynthesize and will have more and better leaf areas, which will certainly have a positive effect on pollutant capture; it is certainly an important part that will significantly affect the result. The fertiliser can be applied to any plants in any place. Within a series of workshops that are part of the CLAIRO project, city representatives will be presented with all the essential information on how to use innovative treatments for new greenery in an urban environment. The main prerequisite for the application of innovative treatment is the improvement of the basic physiological parameters of the new greenery. These will be monitored by a number of highly sensitive and unique methods in order to assess the impact of the innovative treatment on the physiological condition of new plantings and existing vegetation at selected sites and, if necessary, to propose further optimisation of this treatment.

The LI-6400 gasometric device will be used for complex, non-destructive measurements of gas exchange by the plant (assimilation of CO_2, transpiration, conductivity of stomata, etc.) that will be performed simultaneously with the detection of selected fluorescence parameters, especially FV´/FM´ maximum quantum yield and PSII effective quantum yield of photosystem II (Stolárik et al., 2018). The relative content of photosynthetic pigments is determined using SPAD-502 (Konica Minolta Sensing, Osaka, Japan). Fluorescence induction of chlorophyll is also measured directly in the field on the leaves using a PSI FluorPen FP100 pocket fluorometer and a Hansatech Plant Efficiency Analyser fluorometer (Stolárik et al., 2018).

In recent years, we have developed extremely sensitive, efficient and robust tools for analysing endogenous phytohormones by mass spectrometry and monitoring the rate of their biosynthesis. These methods are also applied within the CLAIRO project to monitor the physiological state of existing vegetation and new plantings, depending on the treatment variant. Quantification of endogenous levels of cytokinins and auxins, together with selected stress hormones (abscisic acid, jasmonates, salicylates) and their metabolites is performed by ultra-high-performance liquid chromatography in conjunction with tandem mass spectrometry (UHPLC-MS/MS) with triple quadrupole in positive ESI (+) mode using optimised conditions at selected MRM transitions (Svačinová et al., 2012; Pěnčík et al., 2013; Floková et al., 2014). The results were evaluated in the MassLynx programme and quantified in TargetLynx. Endogenous levels were determined by standard isotope dilution (Novák et al., 2008).

14 DETERMINING VEGETATION CHARACTERISTICS

14.1 CURRENT VEGETATION

A field survey of the current vegetation was conducted at the Radvanice area of interest in August and September 2019. A field survey at the Bartovice site showed that there is no vegetation in the area that would have a significant effect on the capture of pollutants, and the resulting pollutant capture by the current vegetation was determined to be zero.

The vegetation survey at the Radvanice site was divided into grassland habitats and trees. The grassland communities consisted of the species Arrhenatherum elatius and Poa trivialis, reaching an average height of 0.3 m above the surface. Tree species were inventoried as solitary trees or shrubs (solitaire), or clusters of multiple tree species (community). Solitary trees were identified by morphological features. The taxon was determined for all tree species, the height (h) was measured using a digital altimeter with an ultrasonic rangefinder, as well as the mean crown projection (d_k), and the health status was classified on the basis of non-specific symptoms of trunk and crown damage, branching disorders and the occurrence of wood-destroying fungi or rot (Korf 1972; Kandler and Innes 1995). Tree clusters were characterised by the mean stand height, crown diameter and the frequency of non-specific damage (Keller et al., 1997). The projection of the crowns of the tree communities was deducted as the longest axis of the cluster. The characteristics of the current vegetation determined based on a field inventory are summarized in Table 14.1.

Tab. 14.1. Overview of tree characteristics based on a field inventory, Radvanice site.

Identification number	Occurrence	Taxon (dominant)	Crown height (m)	Mean crown diameter (m)	Damage (%)
1	solitary	Salix caprea	12	7	26 – 50
2	solitary	Crataegus monogyna	6	4	11 – 25
3	solitary	Juglans regia	8	7	1 – 10
4	solitary	Juglans regia	13	10	1 – 10
5	community	Juglans regia	12	13	11 – 25
6	community	Crataegus monogyna	10	7	11 – 25
7	solitary	Juglans regia	11	10	1 – 10
8	solitary	Juglans regia	9	6	1 – 10
9	solitary	Crataegus monogyna	8	6	1 – 10
10	solitary	Acer negundo	11	7	1 – 10
11	community	Salix caprea	14	20	1 – 10
12	community	Alnus glutinosa	30	20	26 – 50
13	community	Fraxinus sp.	25	14	26 – 50
14	community	Alnus glutinosa	22	4	11 – 25
15	community	Acer negudo	10	3	1 – 10
16	community	Salix caprea	13	33	1 – 10
17	community	Populus tremula	25	11	11 – 25
18	community	Populus tremula	25	5	11 – 25
19	community	Salix Fragilis	20	6	11 – 25

Individual tree species were positioned on the basis of vectorisation of an aerial orthophoto with a resolution of 0.2 metres, taken in 2018 by the Czech Office for Surveying, Mapping and Cadastre. Their position in the Radvanice area is shown in Figure 14.1.

Fig. 14.1. Overview map of the current vegetation in area of interest A – Radvanice. This map is based on an orthophotomap from 2018 distributed by the Czech Office for Surveying, Mapping and Cadastre. The numbers correspond with identification numbers in Tab. 14.1.

The parameters were used in regression relationships to determine the total content of the leaf area (LA) per m^2, respectively the leaf area index (LAI) per m^2/m^2, as an input for capture models.

For isolated trees, the following relation was used (Nowak, 1996):

$$ln(LA) = -4,3309 + 0,2942 \times h + 0,7312 \times d_k + 5,7217 \times S - 0,0148 \times C, \quad (17)$$

where h was the height of the crown (m), d_k was the mean crown projection (m), S was the mean shading factor, and C was the outer surface of the crown derived from the relation by Gacka-Grzesikiewicz (1980):

$$C = \pi \times d_k \times (d_k + h)/2 \quad (18)$$

The mean shading factor was species-specific and was determined on the basis of tabular data from literature (Nowak, 1996) (Table 10). If a specific tree species was not found in literature, the value of another species of the same genus or family was used. If it was still impossible to assign a value, the mean values of the shading factor for the given group of tree species were used, i.e. 0.83 for deciduous and 0.91 for coniferous species (Nowak et al., 2008).

The following relation was used for a cluster of trees (Nowak et al., 2008):

$$LA = [ln(1 - x_s)/-k] \times \pi(d_k/2)^2, \tag{19}$$

where x_s was the mean shading factor of tree species and k was the light absorption coefficient with a value of 0.52 for conifers and 0.65 for deciduous trees (Jarvis and Leverenz, 1983).

Tab. 14.2. Shading factor values for different tree and shrub species taken from Nowak (1996).

Tree species	Shading factor
Acer Ginnala Maxim. (Amur maple)	0.91
Acer platanoides L. (Norway maple)	0.88
Acer rubrum L. (red maple)	0.83
Acer saccharinum L. (silver maple)	0.83
Acer saccharum Marsh. (sugar maple)	0.84
Aesculus hippocastanum L. (horsechestnut)	0.88
Albizia julibrissin Durazzini (silktree)	0.83
Amelanchier arborea (Michx. f.) Fern. (downy serviceberry)	0.77
Betula pendula Roth. (European white birch)	0.82
Carya ovata (Mill.) K. Koch (shagbark hickory)	0.77
Catalpa speciosa Warder ex Engelm. (northern catalpa)	0.76
Celtis australis L. (European hackberry)	0.92
Celtis occidentalis L. (hackberry)	0.88
Crataegus × Lavallei Herincq. (Carriere hawthorn)	0.89
Crataegus oxyacantha L. (English hawthorn)	0.86
Crataegus phaenopyrum (L.f.) Medic. (Washington hawthorn)	0.76
Elaeagnus angustifolia L. (Russian-olive)	0.87
Fagus sylvatica L. (European beech)	0.88
Fraxinus excelsior L. (European ash)	0.85
Fraxinus holotricha Koehne. cv. Moraine (Moraine ash)	0.78
Fraxinus pennsylvanica Marsh. (green ash)	0.83
Ginkgo biloba L. (maidenhair tree)	0.81
Gleditsia triacanthos f. inermis Schneid. (honeylocust)	0.67
Gymnocladus dioicus (L.) K. Koch (Kentucky coffeetree)	0.86
Juglans nigra L. (black walnut)	0.91
Koelreuteria bipinnata Franch. (Chinese flame tree)	0.9
Koelreuteria paniculata Laxm. (goldenrain tree)	0.81
Liquidambar styraciflua L. (sweetgum)	0.82
Liriodendron tulipifera L. (yellow-poplar)	0.9
Malus spp. Mill. (apple)	0.85
Parkinsonia aculeata L. (Jerusalem-thorn)	0.85
Pistacia chinensis Bunge. (Chinese pistache)	0.85
Platanus × acerifolia (Ait.) Willd. (London planetree)	0.86
Platanus racemosa Nutt. (California sycamore)	0.91
Populus deltoides Bartr. ex Marsh. (eastern cottonwood)	0.85
Populus tremuloides Michx. (quaking aspen)	0.74
Pyrus communis L. (pear)	0.8
Quercus alba L. (white oak)	0.75
Quercus palustris Muenchh. (pin oak)	0.77
Quercus robur L. (English oak)	0.81
Quercus rubra L. (northern red oak)	0.81
Sapium sebiferum (L.) Roxb. (tallowtree)	0.83
Sophora japonica L. (Japanese pagoda tree)	0.78
Tilia cordata Mill. (little-leaf linden)	0.88
Ulmus americana L. (American elm)	0.87
Ulmus pumila L. (Siberian elm)	0.85
Zelkova serrata (Thunb.) Mak. (Japanese zelkova)	0.8

LA values determined in this way were subsequently multiplied by the health coefficient of specific trees based on their classification in one of seven categories (Table 14.3) (Nowak et al., 2008).

Tab. 14.3. Health coefficient according to percentage of vegetation damage.

Health coefficient	**Health**	**Damage (%)**
1	excellent	< 1
0,95	good	1 – 10
0,82	favourable	11 – 25
0,62	poor	26 – 50
0,37	critical	51 – 75
0,13	dying	76 – 99
0	dead	100

Finally, the LA values were applied to the area covered by the vectorised crown of the tree in the orthophoto, and the leaf area index (LAI) per m^2 m^{-2} was calculated. In places where there was no tree cover but the orthophoto showed grassland-herb communities, the leaf area index was assigned on the basis of an expert assessment in the field as equal to 1.

In order for their input into the capture model, the resulting vector LAI layers and vegetation heights were converted to a raster data model at a pixel size of 10 cm using the Polygon to Raster function in ArcMap version 10.7.

14.2 PROPOSED VEGETATION

The characteristics of the proposed vegetation were determined based on the assumed attributes and species composition specified in the planting plan documentation. The following attributes were distinguished: height of the proposed vegetation, species composition and mean crown projection area. The health of the newly planted vegetation was assumed to be excellent, i.e. with no damage. The height of the vegetation was established at 4.5 metres for solitary trees in the vertical canopy layer, 2.5 metres for multi-stemmed trees in the understory, and 0.80 meters for shrubs. The mean crown projection area was established at 4 m.

The spatial arrangement of the vegetation was defined on the basis of planting plan drawings, which were georeferenced into a GIS environment using the boundary points of cadastral parcels. Each tree was vectorised and the above attributes were assigned to them.

Based on these attributes, the input LAI and the height of the stand were determined for the proposed vegetation, as was the case with the current greenery. The LAI was set at 1.5 at shrub planting sites. In places with a herbaceous, shrub and tree layer, all LAI values were added up. The value of the highest point of the vegetation at the given place was used for the stand height. Finally, LAI values for the proposed and current vegetation, inclusive, were determined by the sum of the LAI in both states. The value of the highest point of the vegetation from both states at the given place was used for the stand height (Fig.14.2.).

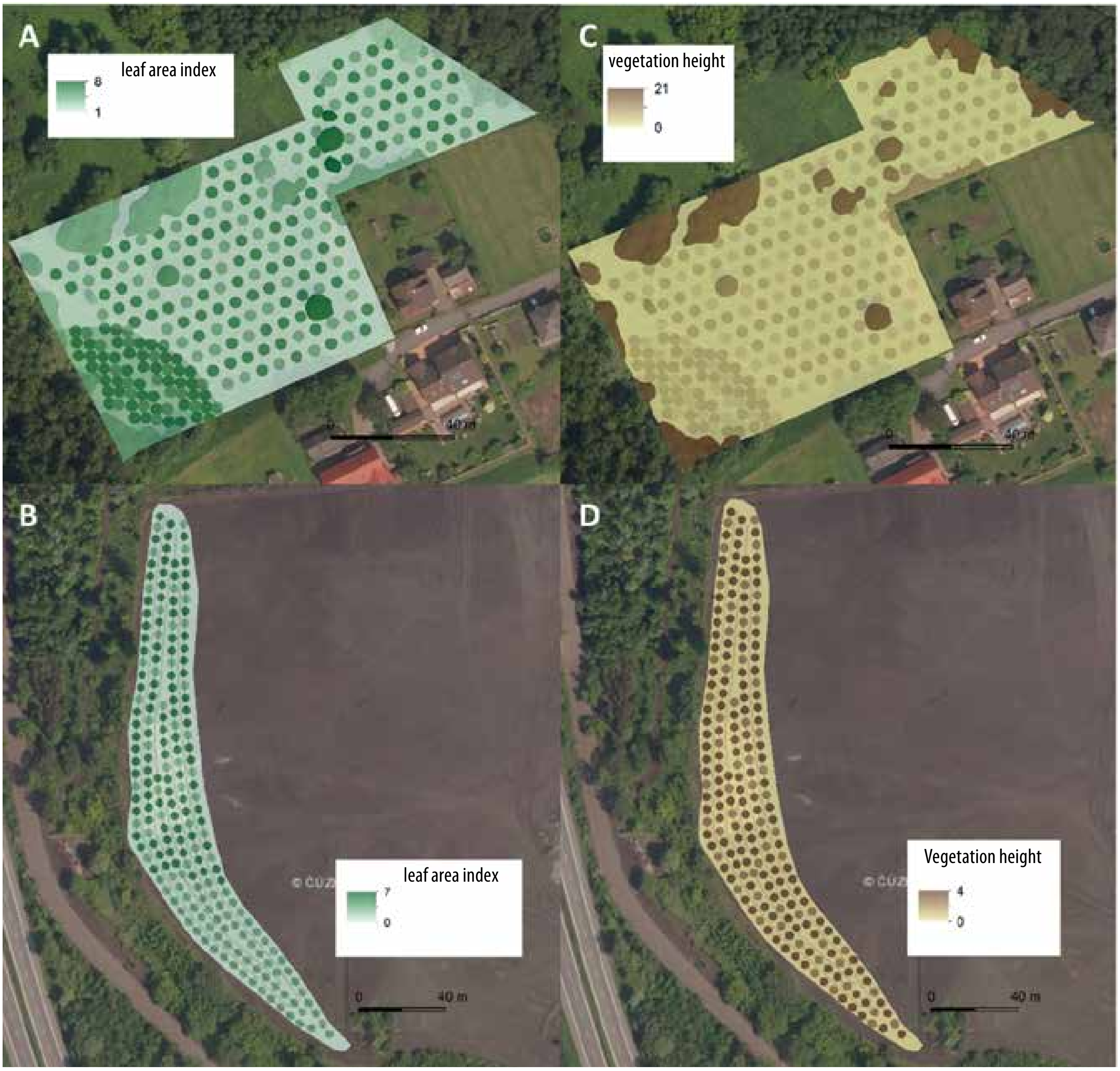


Fig. 14.2. Input parameters LAI (Leaf Area Index m^2m^{-2}), (A, C) and stand height (m), (C, D) for the proposed vegetation (inclusive).

15 CAPTURE OF OZONE, NITROGEN OXIDES AND PM_{10} PARTICLES BY THE CURRENT AND PROPOSED VEGETATION

One of the outputs of the project is a comparison of modelled ozone, nitrogen oxide and PM_{10} particle capture by the current and proposed vegetation. The concentrations of O_3, NO_x and PM_{10}, and meteorological parameters at 15-minute intervals during the period from September to October 2019 measured by sensors, were input into the model. Concentration values were averaged to monthly values for individual sensors and interpolated by the ordinary kriging method using a spherical semivariogram in a 1 x 1 m grid in the defined areas.

The quantification of capture (Q) of the pollutant by the vegetation was calculated according to (Janhäll, 2015):

$$Q = LAI \times F \times T, \tag{20}$$

where Q is the amount of gases and particles captured by vegetation in a certain area and time period (gm^{-2}), F is the deposition flux of gases and particles ($g\ m^2\ s^{-1}$), LAI is the leaf area index ($m^2\ m^{-2}$) and T is the time period (s). The deposition flux (F) of gases and particles was determined from the measured concentrations of these components and from the corresponding deposition rates:

$$F = v_d(z) \times c(z), \tag{21}$$

where v_d is the deposition velocity of the component ($m\ s^{-1}$) and c(z) is the concentration of the component at height z above the ground ($g\ m^{-3}$). The concentration of the individual components was measured by sensors. The deposition rates of gases and particles were modelled using a multiple resistance model from meteorological data and greenery characteristics. A detailed description of the entire calculation is provided in Section 8. Modelling pollutant capture by the vegetation surface. A simplified diagram of the procedure for determining the capture of pollutants by vegetation is illustrated in Fig. 15.1.

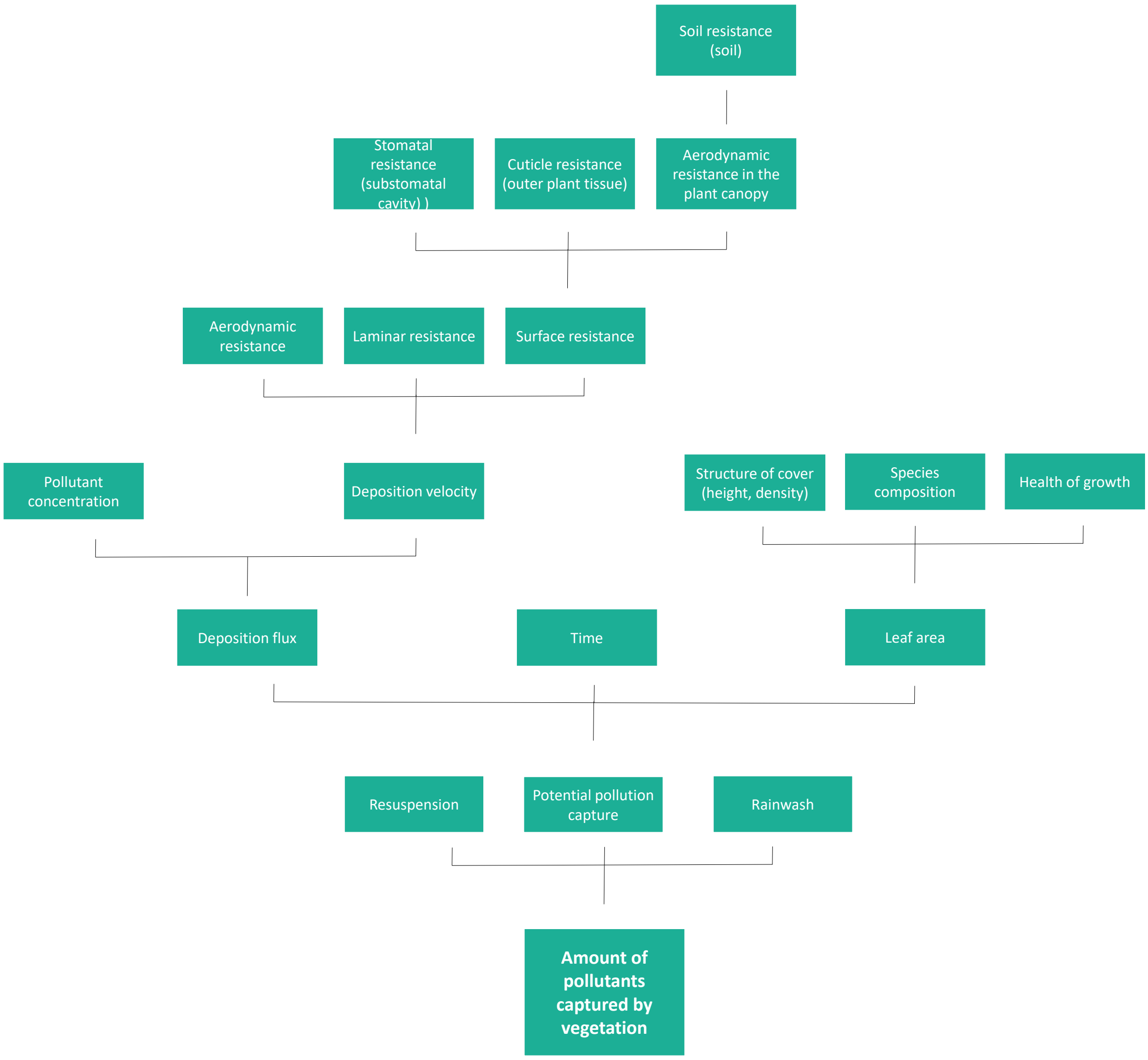


Fig. 15.1. Simplified diagram of the model of pollutant capture by green infrastructure. Adapted based on Zapletal et al. (2011) and Janhäll (2015).

The average air temperature was 13.1 °C, the wind speed was 1.7 m s^{-1}, the relative humidity was 78.1%, the average global radiation was 121 W m^{-2}, the average concentration of O_3 was 71.8 µg m^{-3}, the average concentration of NO_x was 11.4 µg m^{-3}, and the average concentration of PM_{10} was 38.9 µg m^{-3} in September to October 2019 in Radvanice. Fig. 15.2 shows the total capture of O_3 (kg), NO_x (kg) and PM_{10} (kg) by the current and proposed vegetation (simultaneously).

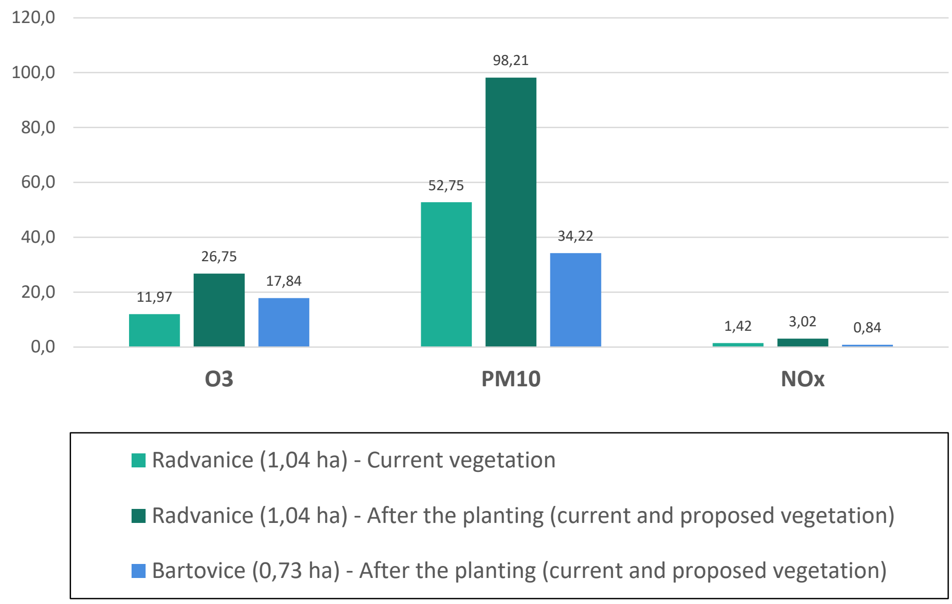


Fig. 15.2. Total capture of O_3, NO_x and PM_{10} (kg) by the current and proposed vegetation at the Radvanice and Bartovice sites.

After the proposed greenery is planted, we can expect a significant increase in the capture of pollutants on the basis of modelled outputs, with over double the amount of capture at the Radvanice site. At the Bartovice site, no significant capture is currently expected before the planting due to the absence of any current greenery. A significant increase in capture is expected after the greenery is planted.

A comparison of the total leaf area of the current (14,869 m^2) and the proposed vegetation (12,044 m^2) at the Radvanice site shows a slightly lower leaf area of the proposed vegetation compared to the current vegetation. In contrast, the pollutant capture by the proposed vegetation was higher than that of the current vegetation. This discrepancy between the total leaf area and the capture of pollutants is due to different deposition rates, or deposition fluxes, depending on the type of vegetation. While the area of interest is currently mostly covered by low, grassy-herbaceous vegetation (Fig. 14.1) with generally low deposition rates, the proposed vegetation only consist of trees of different heights with a shrub layer in the undergrowth (Fig. 12.2). These results indicate the key role of trees in urban environments; even small trees can significantly improve air quality. Fig 15.3 to Fig. 15.5 show the spatial distribution of the capture of ozone, PM10 particles and nitrogen oxides by the current and proposed vegetation at the Radvanice site. Fig. 15.6 to Fig. 15.8 show the capture of ozone, PM_{10} particles and nitrogen oxides by the current vegetation at the Bartovice site.

Fig. 15.3. Capture of O_3 (g) before the planting (on the left) and after the planting of the proposed vegetation (on the right) in a 1x1 m grid at the Radvanice site. Modelled for a two-month period (at the end of the growing season).

Fig. 15.4. Capture of PM_{10} (g) before the planting (on the left) and after the planting of the proposed vegetation (on the right) in a 1x1 m grid at the Radvanice site. Modelled for a two-month period (at the end of the growing season).

Fig. 15.5. Capture of NO_x (g) before the planting (on the left) and after the planting of the proposed vegetation (on the right) in a 1x1 m grid at the Radvanice site. Modelled for a two-month period (at the end of the growing season).

Fig. 15.6. Capture of O_3 (g) before the planting of the proposed vegetation in a 1 x 1 m grid at the Bartovice site. Modelled for a period of two months (at the end of the growing season). No significant capture is expected before the planting due to the absence of any current greenery.

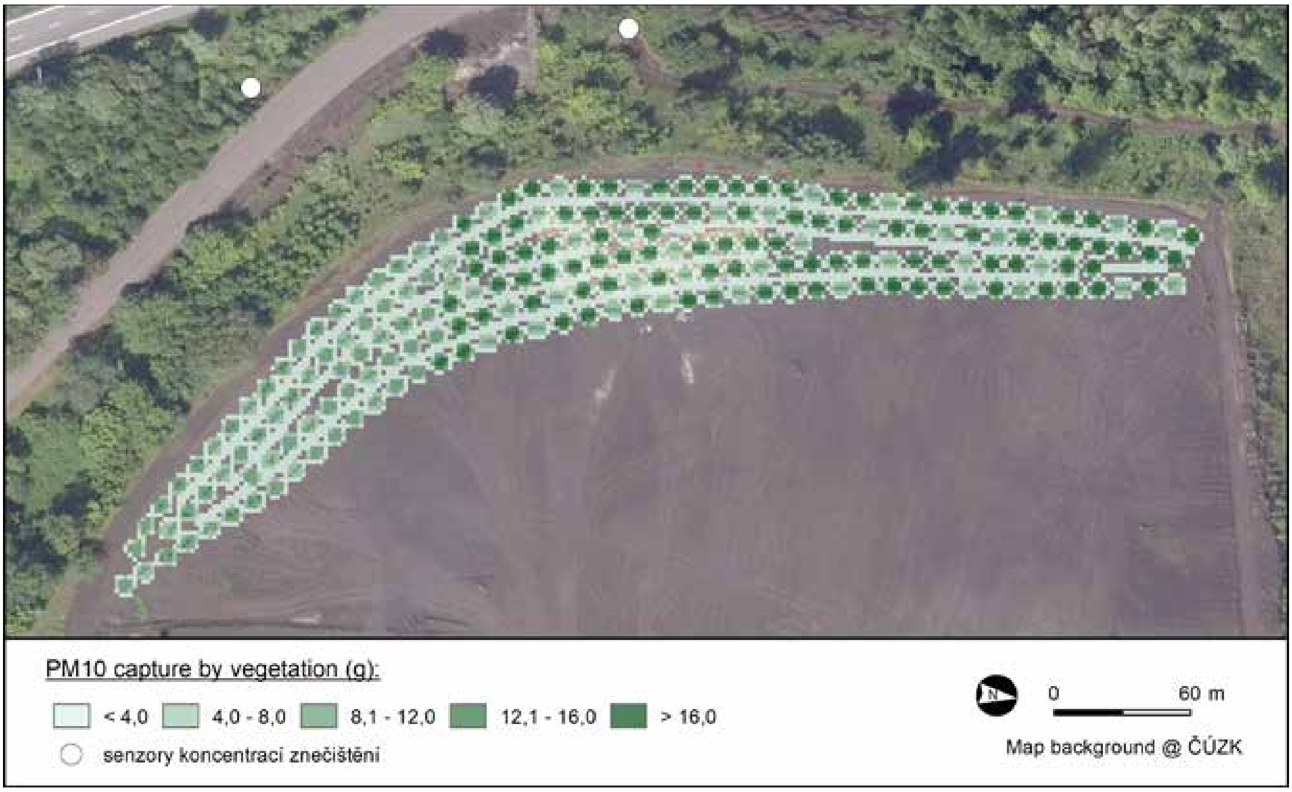


Fig. 15.7. Capture of PM_{10} (g) after the planting of the proposed vegetation in a 1 x 1 m grid at the Bartovice site. Modelled for a two-month period (at the end of the growing season). No significant capture is expected before the planting due to the absence of any current greenery.

Fig. 15.8. Capture of NO_x (g) after the planting of the proposed vegetation in a 1 x 1 m grid at the Bartovice site. Modelled for a two-month period (at the end of the growing season). No significant capture is expected before the planting due to the absence of any current greenery.

16 PUBLIC SURVEYS

Is the topic of air pollution important to inhabitants of the Moravian-Silesian Region? How would people describe the quality of the air in their area? The answers to these and other questions were found by interviewers on streets of the Ostrava agglomeration in mid-October 2019 and in the same period in 2020.

One of the aims of the questionnaire survey was to determine whether people in the region are willing to change their lifestyles to improve the air quality and, if so, how specifically. Would they use ecological heating, travel by public transport more often, or participate in planting greenery? With further questions, the interviewers tried to find an answer to how important greenery is to the inhabitants, whether they would welcome new solutions such as vertical gardens, green facades, green roofs and the like, and whether they would contribute financially or plant their own greenery.

During the survey, respondents received detailed information about the sources of pollution in their area, examples of different variants of urban greenery, information about the CLAIRO project and the importance of plant composition and the method of planting, which can affect air quality and mitigate climate change.

16.1 DEFINITION OF THE PROBLEM

For further effective transfer of outputs from the CLAIRO project to the general public, it is necessary to know the current views of inhabitants and their willingness to accept new information in the field of air protection. This does not just include passive forms, but also attitudes and opinions, active approaches, definition of the right target groups and their size.

16.2 TYPE OF RESEARCH

Descriptive research, which provides a basic picture of selected aspects of the researched problem in a given period, describes the phenomena and processes relevant to decision-making.

Quantitative research was chosen to analyse the behaviour of customers. The research was conducted using exclusive quantitative research with face-to-face standardised in-home interviews.

With its research methods and the qualification of the obtained data, quantitative research allows us to reach the required conclusions (Malhotra et al., 2012). The research will be conducted using the PAPI (Paper And Pencil Interviewing) method. The main advantages of this interview method include the ability to control the subsample (quota sampling). Interviews are considered the most appropriate method to fulfil the objectives of this study, mostly because they ensure the representativeness of the data obtained. Possible disadvantages of primary data collection may include a limited number of questions. In contrast, the advantage of the chosen method is the interviewer's ability to check the truthfulness of respondents' answers, as he is present during the interview, and the ability to influence the structure of the subsample (Saunders et al., 2012). The advantage from the perspective of the project was also the possibility to directly inform the respondents about the existence of CLAIRO and ongoing activities.

Implementation phase:

Data was collected:
in 2019 - 15 October 2019 - 10 November 2019
in 2020 - 5 October 2020 - 31 October 2020

16.3 DEFINITION OF THE SAMPLE AND SUBSAMPLE

The research sample consisted of inhabitants of the Ostrava agglomeration over the age of 18. Respondents were selected based on predetermined quota in order to ensure the representativeness of the subsample. Established quota: 1) gender, 2) age, 3) residence.

16.4 SUBSAMPLE

The subsample consisted of a total of 1207 respondents. The data were processed using standard statistical methods and professional software. Second-level data sorting was used based on demographic questions as well as other behavioural indicators.

2019 survey

605 respondents from selected towns and villages of the Ostrava agglomeration, specifically from towns (and small nearby villages): Bohumín (40), Český Těšín (40), Frýdek – Místek (60), Havířov (60), Karviná (60), Opava (40), Hlučín (20), Ostrava (240), Třinec (42)

2020 survey

605 respondents from selected towns and villages of the Ostrava agglomeration, specifically from towns (and small nearby villages): Bohumín (24), Český Těšín (35), Frýdek – Místek (52), Havířov (81), Jablunkov (15), Karviná (52), Opava (40), Orlová (20), Ostrava (236), Třinec (51)

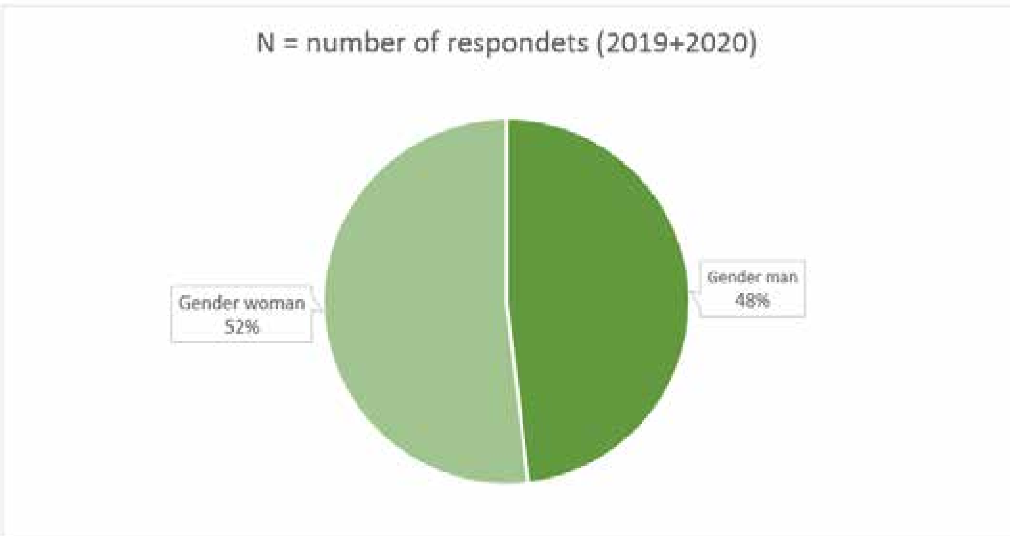


Fig. 16.1. Structure of the subsample - according to gender.

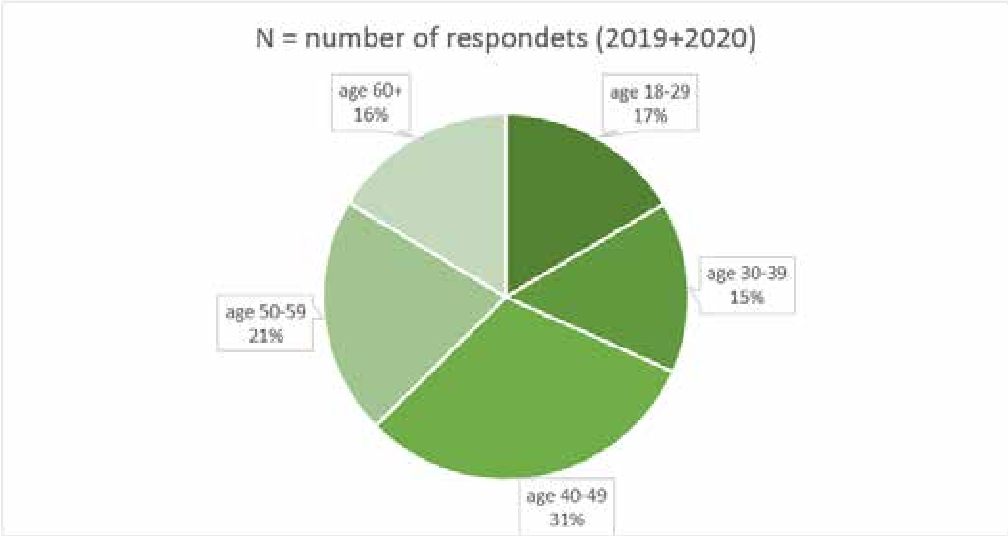


Fig. 16.2. Structure of subsample - according to age.

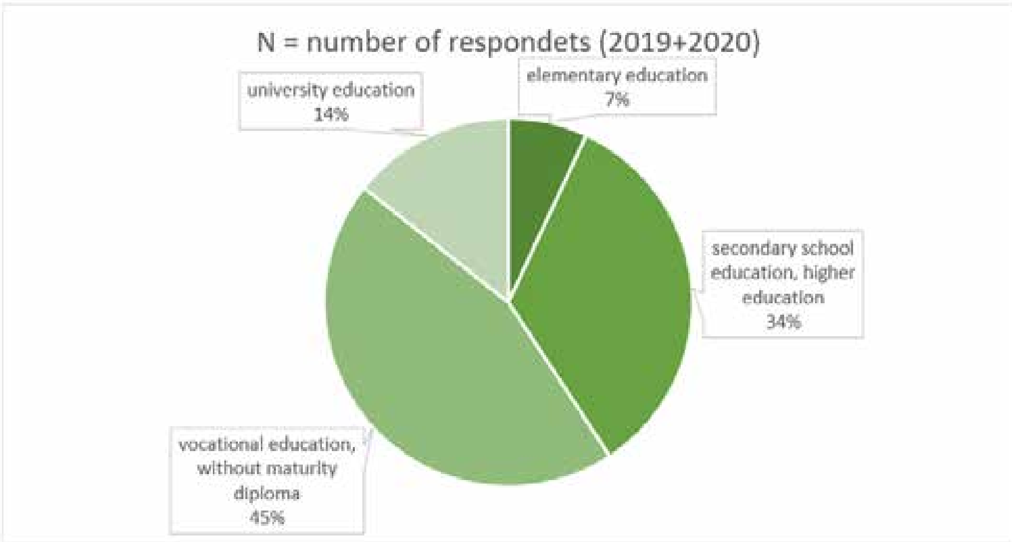


Fig. 16.3. Structure of subsample - according to education.

17 OUTPUTS OF PUBLIC SURVEYS

The public survey was followed by a study entitled 'The public's attitude towards air pollution and urban greenery, and their willingness to change their behaviour in favour of air protection' (hereinafter the 'Study'), which aimed to summarize the most important results of both surveys and provide a recommendation for cities and interest groups in the area in the field of air protection and urban greenery. The main goal of the Study was to give villages and towns in the Moravian-Silesian Region feedback from their inhabitants on topics that residents themselves consider important, and to provide expert advice on what can be done in this area and how to use the potential and interest of residents to participate in these policies. Feedback should be provided in a concise, easy to read and attractive form that will help increase interest in the topic of public participation in air protection.

17.1 MERGING OF OUTPUTS FROM 2019 AND 2020 SURVEYS

The differences in responses in the two surveys were not significant, so the study is based on aggregate figures. The answers that represented an obvious shift in opinion are listed in the comments.

The study was divided into four basic parts:

A. Air
B. Urban greenery
C. The willingness of inhabitants to change their behaviour in favour of air quality
D. Conclusions and recommendations for towns and villages

An expert in the surveyed area commented on each section. The experts that were addressed, who confirmed their interest in cooperating in the study, received detailed information about the 2019-2020 survey. Based on the survey outputs, they prepared comments on the relevant sections of the study and recommendations for towns/villages on how to further cooperate with the public in these areas. Based on meetings with the CLAIRO project staff (specifically SOBIC and RSTS partners), the main conclusions of the study based on the public survey were consulted and drawn. The comments by each expert are cited in the introduction of relevant sections of the study.

Survey outputs were divided according to numbers and questions as follows:

A) AIR

1. Are you interested in the topic of air protection and is it important to you?

2. How satisfied are you with the quality of the air where you live?

3. How do you view the current air quality where you live in comparison with air quality 10 years ago?

4. Do you think that the government's investments in air protection are showing results (e.g. boiler subsidies, dedusting of industrial enterprises, lower tax burden on ecological resources)?

5. What form of air pollution do you think affects the air quality in the Moravian-Silesian Region most? Please estimate the percentage of individual sources, which should add up to 100%.

6. What problems do you think are currently most serious?

7. I fully trust/I trust the media and reports on air quality and the environment, but I verify them/I don't trust them

8. Do you want regular information about air protection in the Moravian-Silesian Region?

B) URBAN GREENERY

9. How specifically are you willing to contribute to better air quality? (By supporting greenery)

10. Would you be willing to contribute to your village financially (e.g. once a year) for planting greenery or another form of air protection support?

11. Which of these solutions would you personally support? (Note: link to air pollution)

12. Do you like these ideas? Would you support the construction of these natural solutions in your area?

13. Do you think that the composition and structure of planted greenery (what and where you plant it) can affect air quality? (Note: The aim of this question was to point out the CLAIRO project. An informative leaflet was included)

C) THE WILLINGNESS OF INHABITANTS TO CHANGE THEIR BEHAVIOUR IN FAVOUR OF AIR QUALITY

14. Are you willing to contribute to improving the air quality and the environment in your region?

15. How specifically are you willing to contribute to better air quality?
    Ecological heating (by replacing the boiler, increasing efficiency, choosing better fuel, etc.)
    By using sustainable forms of transport - public transport, bicycle, carpooling, etc.
    By supporting greenery planting
    By not burning household waste

16. Have you ever considered moving because of air pollution?

17. In what way does air pollution limit or trouble you most?

The most important finding is that:

- Almost 30% of inhabitants in the region believe that the air quality has worsened in the last 10 years, which does not correspond with actual air quality measurements.

- The topic of air quality is important to four fifths of inhabitants of the agglomeration. Almost one half of inhabitants are somewhat or definitely unsatisfied with the air quality.

- An overwhelming majority of respondents declare their willingness to personally contribute to improving the air and environment in their region, most often by supporting the planting of greenery (90%) and not burning household waste (including leaves, grass, paper), but also by using sustainable forms of transport.

- The topics of clean air and greenery in cities are especially important to university-educated and younger inhabitants, which is an important message for cities facing an outflow of population mostly from this group. Although we are facing this outflow in our region, we should also take advantage of the fact that there are universities in cities (Ostrava, Opava, Karviná), as it is young and educated people who produce leaders in thought and politics.

17.2 CONCLUSIONS AND RECOMMENDATIONS FOR TOWNS AND VILLAGES

The final section titled 'Conclusions and recommendations for towns and villages' was not based on the conclusions of the survey, but on the recommendations of experts. These recommendations contain references to other professional publications, public surveys conducted in other cities, and examples of successful projects that address the issue. All references are included in the following section of the Study (available for download on the CLAIRO website at www.clairo.ostrava.cz).

18 CONCLUSION

Green infrastructure improves the environment with its filtering, cooling, protective and social functions. It contributes to the improvement of air quality in urban environments by removing suspended particles and other pollutants by capturing them on the leaf surface. Green infrastructure, planted and treated with regard to its sensitivity to pollution and its ability to capture pollutants from the air, can be a suitable adaptation solution for improving air quality in places with heavy air pollution.

The present methodology, including a case study of greenery planting in Ostrava Bartovice and Radvanice, provides the basic principles of establishing green infrastructure in industrial areas to mitigate the impacts of environmental change through nature-friendly management. The expansion of green infrastructure in cities is one measure that a large part of the population welcomes and is willing to take part in. This is potential that cities should work with more in the future, not only in terms of air quality.

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