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Using Urban Greenery to Improve Air Quality

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General context

Urban air pollution

Outdoor air pollution is a major environmental health problem affecting almost all of the global population, as around 99% of the world's population live in places where air quality levels exceed the guideline limits of the World Health Organization.[1]

According to the estimation of WHO, air pollution, that is the leading environmental cause of mortality globally, kills annually approximately 7 million people worldwide[2]. There are also some more pessimistic estimates linked to the death toll from air pollution. In line with the results of a study published in April 2021 by the University of Birmingham and the Harvard University over 10 million premature deaths are attributable to fossil fuel combustion alone per year[3]. Far more than the estimated 1.3 million people who die each year as a result of road traffic accidents[4].

This mortality is mostly due to exposure to fine particulates[5]. But there are serious risks to health also from exposure to ozone, nitrogen dioxide and sulphur dioxide[6]. The air pollution related premature deaths are mostly a result of increased mortality from chronic diseases[7].

In Europe, a significant proportion of the population lives in areas where pollution poses serious health risks according to the European Environment Agency. Around 90% of city dwellers in Europe are exposed to pollutant concentrations that are considered harmful to health[8].

In 2021 there were 31 infringement procedures in place against 18 EU Member States related to compliance with air quality standards[9]. These infringement cases are predominantly linked to failures in meeting legal targets for nitrogen dioxide and particulates[10]. In the EU, mainly road transport is responsible for emissions of nitrogen oxides, while particulates are mostly emitted by the residential, commercial and institutional sectors, primarily linked to domestic heating[11, 12].

Impacts of air pollution on health

Air pollution is a major contributor to chronic diseases, including cardiovascular diseases, chronic obstructive pulmonary disease, asthma and lung disease[13]. In 2016, according to WHO estimates, globally almost 60% of outdoor air pollution-related premature deaths were due to cardio-vascular diseases, including heart disease and stroke. A much lower proportion, 18% of deaths were due to various respiratory diseases and 6% were attributable to lung cancer[14]. In 2013, air pollution and in particular PM was classified by the International Agency for Research on Cancer as a leading cause for cancer[15].

In Europe the total excess mortality rate attributed to air pollution is estimated to be nearly 800 000 per year. At least 48% of this mortality is due to cardiovascular diseases, such as coronary artery disease (ischaemic heart disease) and stroke. In addition, a fraction of other non-communicable diseases should also be counted to cardiovascular diseases related mortality (See *Figure 1*)[16]. There is an indication that air pollution has inflammatory effects on the heart, and also has a role in high blood pressure and diabetes[17].

In the EU, according to the European Environment Agency, 379,000 premature deaths were attributable to fine particulate matter (PM2.5) in 2018. This is an order of a magnitude more premature deaths compared to those ones that were linked to nitrogen dioxide (54,000) or ozone (19,400)[18].

The most harmful pollutants to human health are ultrafine particles (UFP), that are smaller than 0.1 micrometres in diameter. UFPs, because of their extremely small size can penetrate deep into the lungs and can even pass through the lung tissue into the bloodstream[19]. They primarily originate from man-made sources, such as combustion of gas and coal, biomass burning, automobile traffic and industrial emissions[20].

Research of the British Heart Foundation has indicated that fine particulate matter can stay in the bloodstream for several months, damaging the blood vessels and increasing the risk of blood clots, leading to stroke or heart attacks[21]. Even course particulates (PM_{10}) can cause various health problems, including high blood pressure, and asthma[22].

Ozone pollution can cause coughing and sore throat, can damage the airways, make breathing difficult and aggravate respiratory diseases[23]. Nitrogen dioxide exposure has similar health effects, as it can irritate the airways and can exacerbate respiratory diseases, and particularly asthma. Longer exposures can contribute to the development of asthma[24].

In addition to adverse health effects, air pollution was found to be associated with higher crime rates. Even moderate pollution was found to increase crime[25]. A study undertaken in the United States led by Jackson Lu linked air pollution with various types of crime, such as manslaughter, rape, robbery, theft, car stealing cars and assault[26]. These effects on criminal behaviour can be explained by increased anxiety triggered by air pollution, as well as pollutants damaging brain structure and neural connections[27].

Furthermore, exposure to air pollution was found to be linked to the rise of depression[28], a higher risk of psychotic episodes, such as paranoia[29], and to increased risk of dementia[30].

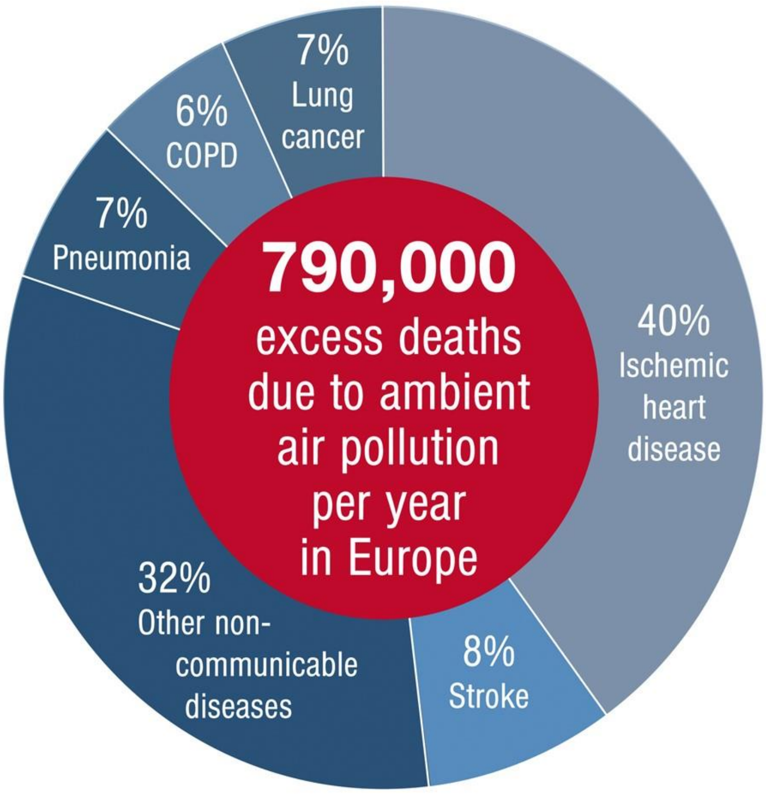


Figure 1: *Estimated excess mortality attributed to air pollution in Europe, broken down by disease categories*
Source: © 2019, Oxford University Press on behalf of the European Society of Cardiology
(COPD: chronic obstructive pulmonary disease)

The potential of greenery to reduce concentration of air pollutants

Urban green infrastructure can bring about positive health outcomes through reducing the public's exposure to air pollution. The use of greenery can offer options for mitigating air pollution that can effectively complement conventional emission control strategies. Vegetation plays an important part in controlling the flow and distribution of pollutants.

In general, the adverse impacts of air pollution can be reduced through the application of three basic methods:

- *Reducing emissions at source*. Measures linked to this method include using less polluting industrial processes, using less polluting raw materials, improving process efficiency, emission control technologies, traffic calming, emission controls on vehicles, or use of cleaner fuels. This method should be prioritized, since reducing emissions is the most effective way of mitigating exposure to pollutants.
- *Extending the distance between pollution sources and receptors*. The concentration of pollutants decreases with distance from the source as pollutants are mixing with cleaner air.
- *Protecting receptors*. This method has to do with direct interventions targeting reduced concentrations at the receptor site.[31]

Green infrastructure can help to varying degrees in the application of all three methods. By placing vegetation as barriers, the distance between sources and receptors can be *extend*ed virtually. Hedges acting in this role can be used as green buffers separating vehicles and pedestrians. Greenery can also *protect* people from air pollution, through increasing the deposition rates of pollutants with the help of the relatively large surface area of the plants[32]. Urban green spaces can even help in reducing emissions indirectly, through taking the place of emission sources, or through encouraging less polluting active transport[33].

Processes influencing air quality

Urban greenery can protect people from air pollution through two key processes, dispersion and deposition.[34]

Dispersion is a process through which air pollution is distributed into the atmosphere. Urban vegetation, with its dispersive effect, changes the speed of pollutants and also the distance pollutants travel before they reach people. This can lead to significant reductions in the concentration of pollutants locally[35].

Trees and hedges by providing obstacles to the airflow, introduce turbulence, increasing the dilution of pollutants. As a result, the distance between the source and receptor will be virtually extended. The introduction of a vegetation barrier displaces the flow of pollutants upwards, extending the effective path-length of air from source to receptor, while dilution is promoted[36].

In an open-road environment a vegetation barrier (i.e., a hedge) can halve the concentrations of pollutants in its immediate vicinity[37]. The introduction of hedges between road and pedestrians are particularly effective in reducing pollutant concentrations through dispersion. A study of the University of Surrey indicated that hedges along roadsides can cut back the concentration of black carbon, key component of fine particulate matter, by up to 63%. It was also confirmed by the study that hedges or a combination of trees with hedges are the most effective forms of greenery for reducing exposure to pollution emitted by cars[38]. Smaller reductions were shown for gaseous pollutants[39].

Deposition is a process by which pollutants land on solid surfaces and are removed from the air[40]. Green infrastructure can reduce the concentration of air pollutants locally by enhancing their deposition rates, since pollutants deposit more efficiently on vegetation than on smoother artificial surfaces[41]. Trees and shrubs have a relatively high surface area that can function as natural sink for pollutants. The rate of deposition is subject to the available surface area as well as the aerodynamic roughness of the surface[42].

Apart from dispersion and deposition there is a third mechanism, the modification of particulate matter, through which green infrastructure can improve air quality. These modifications include the coagulation of smaller particles that may accelerate deposition, and the changing of pollutant compositions that may reduce the toxicity of particulate matter[43].

Leaf-associated microbes, such as bacteria, yeasts, and fungi have a role in bioremediation (phylloremediation) of air pollutants. Microbial communities colonizing the surface and the interior of plants' leaves were found to be able to adsorb and biodegrade or transform pollutants into less toxic molecules.[44]

Practical approaches to reduce air pollution with the use of greenery

Some trees are far more effective at trapping air pollutants than others[45]. A number of vegetation traits needs to be considered for the selecting appropriate plant species for pollutant capture.

The filtering activity of trees depends mainly on the canopy size. Not surprisingly, larger canopies can trap more pollutants than smaller ones[46]. The density of the foliage is a key factor as it actually determines the vegetation area available for deposition[47]. The density of a tree is influenced by the branching of the crown and the characteristics of the leaves[48]. Although vegetation density increases deposition, still a green filtration barrier should not be too dense to allow penetration and to ensure that the airflow is not directed above the barrier limiting opportunities for deposition[49]. An optimal vegetation barrier density will permit infiltration without throughflow[50].

Mature trees with large canopies are significantly more efficient in removing pollutants compared to young trees[51]. Research indicates that large, healthy trees with a trunk diameter above 75 cm remove more than 70 times more air pollution than small, healthy trees with a trunk diameter below 25 cm[52].

Apart from the height of a tree and foliage density, the shape of the crown is also relevant. A spherical crown for instance is found to be more effective than one with a pyramid shape[53].

Foliage longevity is another important aspect. As opposed to deciduous trees, which lose their leaves during winter, evergreen species can act as year-round filters[54, 55]. However, evergreen species may be more sensitive to certain environmental stressors, such as draught and heat[56]. Among deciduous species those ones are preferable that exhibit longer in-leaf seasons[57].

There is an indication that species with smaller leaves tend to be more effective than ones with larger leaves. Conifers with their dense canopy of needles seem to support more effectively deposition of particulates than deciduous species.[58]

The features of leaf surface also influence the filtration potential of plants. Rough, hairy and rugged surfaces that include grooves and ridges act as the best biofilters for particulates[59, 60]. The stickiness of the leaves was also found to be significant in trapping particulates[61]. Due to their hairy leaves, silver birch, yew and elder are particularly effective at capturing ultrafine particles, which can pose substantial hazards to human health[62].

Stomata that are the small pores found on leaf surfaces controlling gas exchange, have a relevant role in pollutant capture, particularly in case of gaseous pollutants[63]. Air pollutant removal may be enhanced by the selection of species that have stomata with extensive opening periods, such as poplar and some oak species[64].

Not only the structure and other properties of the leaves are relevant for particle capture efficiency, but also the canopy shape and shoot structure. There is an indication that tree species with more complex shoot structure have higher particle capture efficiency.[65]

Despite its ability to capture air pollutants, greenery can also be a source of pollution. Trees and other plants produce volatile organic compounds, which when exposed to sunlight react with nitrogen oxides emitted mainly from vehicles and industrial sources to form ozone, that can lead to the formation of ground-level smog. In addition, many tree species produce pollen, which can cause allergic reactions.[66] When planning urban greenery in the vicinity of residential areas, it is wise to avoid planting tree species that produce highly allergenic pollen, such as birch, ash, oak, and elm[67], or those ones that emit significant amount of volatile organic compounds, such as black locust, poplar or plane tree[68].

Various beneficial vegetation traits that influence capture efficiency does not automatically make certain plant species fit for any context. Simply selecting tree species that have a high potential for air pollution mitigation will not lead to desirable results. When designing greenery for pollutant capture, plant species should be selected that are adapted to the local environmental conditions. In urban settings, and particularly in roadside environments, vegetation has to cope with multiple stressors, such as dry or poor soil conditions, various diseases, soil compaction, lack of root space, excess water in the root zone accompanied by anaerobic conditions, air pollution, or salt pollution[69]. Considering these extreme conditions in urban systems, when assessing the suitability of various species, it is plants' stress tolerance that should be given priority over all other functionalities[70].

Box 1 - Urban forests planted in Ostrava to improve air quality

The CLAIRO project under the Urban Innovative Actions initiative of the European Union aims at the systematic reduction of air pollution through comprehensive planning and planting of greenery with a positive impact on air quality. Under the project new greenery was planted in Ostrava, Czech Republic in 2021 that is aimed to function as a living lab for cities in the Upper Silesian metropolitan area and beyond, providing long-term information on air quality improvement. The vegetation was installed in two plots located in the most polluted neighbourhoods of Ostrava, close to a metallurgical plant. The design of the composition and structure of the greenery was supported by measurements of air pollutants and climatic conditions. The long-term goal is to share with other districts and cities the novel experience gained at the urban greenery living lab, and to inspire them with innovative green solutions.

The detailed design of the greenery structure and composition was finalized in summer 2020. The objective was to establish communities of trees and shrubs that form continuous and dense canopies to allow effective filtration of the air.

Communities of multiple plant species with similar ecological needs were specified that correspond to the habitat conditions of the target sites. Maximizing leaf surface that allows increased pollution deposition was an important consideration in the selection of the species. Preference was given to species with a densely branched crown and a large volume of green matter, as well as to evergreen tree species that can catch pollution all year round. The new vegetation has two tree layers and a shrub layer in order to maximize the canopy density and through this filtration efficiency. In addition, species with increased resistance to air pollution were preferred.

At the two target sites, which are located next to an industrial area, the newly planted trees are exposed to air pollution and other abiotic stressors. To increase their tolerance to air pollutants and contamination, as part of an experiment, the soil and the plants are treated with specific preparations that contain plant hormones.

Modelling results indicate that with the designed vegetation the capture of particulates at one of the target sites is expected to almost triple as compared to the initial state.

Source:
https://uia-initiative.eu/en/uia-cities/ostrava[71]
Image: City of Ostrava

Design considerations

A guide titled, 'Using green Infrastructure to protect people from air pollution' published by the Greater London Authority[72] provides a range of practical recommendations for designing greenery for reductions in exposure to urban air pollution. Depending on the type of urban road the guide provides help in the identification of the appropriate type of green infrastructure intervention. The guide highlights the relevance of careful design, as in certain urban situations wrongly placed vegetation can even increase locally pollution concentrations. Some of the key recommendations of the guide are summarized below:

- On busy roads surrounded by buildings on each side (street canyons), where the air is more polluted at street level than above, a dense row of trees can have an adverse effect on local air quality, as the trees can trap the pollution emitted from vehicles under their canopies. In such urban situations, vegetation barriers between the vehicles and pedestrians, such as hedgerows, can be effective in reducing pollutant concentration at the receptor side.
- On very quiet street canyons where air is more polluted above the buildings than at street level, a dense tree alley with extensive canopies can effectively reduce downward dispersion, protecting people at street level.
- On open roads, when the aim is to protect people right next to the road, hedges can function as effective barriers between the road and pedestrians (*Figure 2*). As the height of the vegetation barrier increases, the protected area increases.
- When the goal is to protect people further away from an open road, a taller barrier, such as a dense row of trees with hedges, can be useful to reduce concentration of pollutants in a larger area.
- Green open space next to a road, such as a park has an essential role in reducing exposure to pollution from transport, as it allows pollutants to disperse.
- A thicker vegetation barrier will be more effective at displacing road transport emissions and at supporting their dilution.

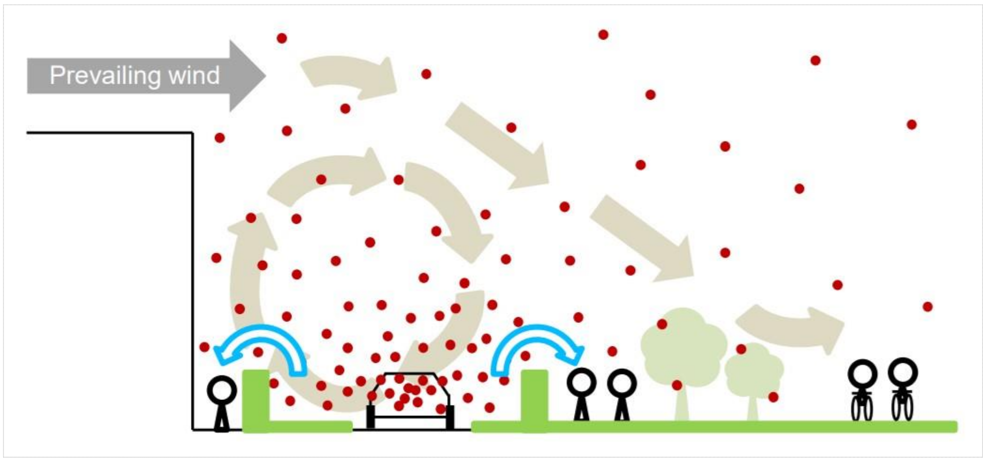


***Figure 2**: Protecting people with hedges at the side of an open road*
Source: Greater London Authority, 2019

Different foliage density is desirable depending on whether the greenery is used for dispersion or deposition. As the density of the barrier decreases, the effective path-length shortens and with this the dispersive effect of the vegetation decreases, but at the same time the opportunity for pollution removal through deposition increases[73]. The denser the vegetation barrier, the more effective it will be at displacing and diluting the polluted air. Therefore, green barriers used for dispersion should be as dense as possible[74, 75]. In contrast, vegetation barriers that aim at the filtration of pollutants should be sufficiently dense to promote deposition with an extensive surface area, while at the same time should not be overly dense, to support penetration, instead deflecting the airflow[76].

Hedges are particularly effective in protecting schoolgrounds, kindergarten yards, and playgrounds from air pollution exposure (See *Box 2*). Evergreen species are proposed for vegetation barriers by a study undertaken by the University of Surrey[77], which can effectively reduce exposure to air pollution in all seasons.

Box 2 - Green screens and hedges protecting schools from air pollution in London

Channel 4's Dispatches programme together with researchers from Kings College and Queen Mary University implemented a set of measures linked to green infrastructure interventions to reduce exposure of schoolchildren to air pollutants at Lordship Lane Primary School in London.
Under the scheme 1.8 meter high and over 1-meter-wide ivy screens were installed around the perimeter of the school playground to absorb pollutants. The plants on the ivy screen are grown on steel frames. In the playground evergreen hedging plants were supplementing the screens.
Before the intervention, NO_2 levels were over 50% higher than recommended levels around the school. Laboratory testing indicated the presence of sooty particles in the children's lungs. After the installation of the new greenery, pollution levels were reduced by 53% in the playground, while the concentration of pollutants still remained high around the school. In addition, laboratory tests showed that pupils had benefitted from reduced exposure from pollutants.
Under a targeted program, 29 schools are supported across London to install barriers made of plants and hedges around primary school playgrounds to combat air pollution.

Sources:
https://www.hedgesdirect.co.uk/acatalog/how-hedging-can-help-reduce-air-pollution.html[78]
https://futureclimateinfo.com/air-pollution-invest-now-to-safeguard-our-children/[79]
https://www.standard.co.uk/futurelondon/cleanair/air-pollution-london-sadiq-khan-a4054416.html[80]
Image: Hedges Direct

Green roofs and green walls can also remove large amounts of pollutants from air. While trees can trap pollution under their canopies in certain urban situations, green roofs and walls let the air circulate freely and at the same time can remove pollutants[81]. A study conducted in Australia indicated that green roofs can contribute to emission reductions ranging from 35% to 83%[82]. Green walls in street canyons were found to reduce PM_{10} concentrations of by up to 50%, and NO_2 concentrations by up to 35%[83].

When greenery is designed for deposition, a number of factors need to be considered. One key aspect is the height of the vegetation. Low grasslands have the weakest, while coniferous forests have the strongest filtering potential. In between, filtering effect increases in the following order, high grassland, shrubs and deciduous forests. Research has shown that transitions in the landscape from low vegetation to forest also have a significant effect on the deposition process of air pollutants. Because of an 'edge effect', deposition in the centre of a forest is significantly lower than in the fringe zone. Deposition will increase further and the deposition zone will grow if the transition in the woodland fringe is sharp.[84]

Box 3 - Using street-level air quality data to improve urban design in Copenhagen

In Copenhagen as part of a unique initiative Google's Air View data was combined with Gehl Architects' data on the everyday movement of children and day care workers, and based on this urban design solutions were suggested to reduce exposure to air pollution and to increase access to better air quality.

In 2013 Google started to develop the Air View Project in order to measure street-by-street air quality in cities. For measurements Google Street View Cars were used that were equipped with air quality sensors. Such detailed measurements have shown that air pollution differs street by street sometimes up to 5-8 times within a city block. Under a related research heart diseases were found to be related to street-level variation of air quality. The results have indicated that hyper-local maps of air pollution can be useful for supporting policies to reduce air pollution

In 2018 in a collaboration with Gehl Architects, Google started measuring air quality in Copenhagen to build an annual average street by street map. Gehl was tasked in the project to operationalize the air quality data by assessing the everyday movement of children and day-care workers. Gehl mapped childcare institutions and playgrounds in the Vesterbro neighbourhood and studied where small children move through the city. The mapping has shown that a lot of children move through streets with really poor air quality.

Under the project, busy areas with poor air quality were identified in Vesterbro, where the aim was to reduce exposure to air pollutants. For such areas Gehl proposed traffic calming measures, the removal of parking, and the installation of green buffers as pollution barriers.

At the same time areas with better air quality were also identified, where small children could be invited to spend more time. A concept was developed for such areas, featuring wider sidewalks and new greenery to make the place more welcoming, as well as narrow roads to lower car speeds.

Sources:
https://gehlpeople.com/projects/air-quality-copenhagen/[85]
https://www.uu.nl/en/news/project-air-view-measurements-result-in-hyperlocal-map-of-air-quality-in-copenhagen[86]

Urban planners can also use green infrastructure to invite residents to spend more time in public spaces with better air quality. (See *Box 3*) Such areas can be made more welcoming and comfortable by adding new greenery[87]. Parks can protect people from air pollution indirectly by attracting them away from polluted areas into cleaner ones[88]. When designing streets, people could be encouraged by adding greenery to stay longer in the mid-sections of the streets and away from street corners[89], as intersections are typical pollution hotspots in a city[90].

Green corridors and parks promote ventilation within the urban fabric and through this can help improve air quality. Strategic urban planning can enhance the natural circulation of air in a city. Designed in line with natural wind patterns, green corridors create air pathways that can reduce pollution in stagnant air[91]. Ventilation in a city can be supported by the creation of wide linear parks[92], by the use of construction bans at strategic places (such as valleys, hills, hillsides, and saddle-like topographies)[93, 94], and by the development of a grid of parks and small green areas that are connected to one another[95] (See *Box 4*). The greenery in ventilation corridors should be planted in a less compact arrangement, to make it possible for the wind to pass through them[96].

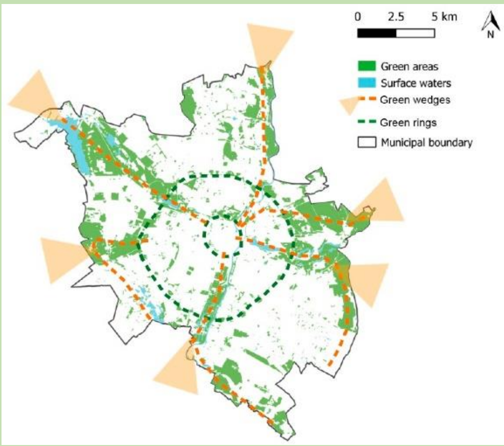
Box 4 - A massive wedge-and-ring greenery system helps ventilation in Poznan

Poznan has a well-established green infrastructure that is defined as a wedge-and-ring greenery system. The green wedges follow the main watercourses in the city, the Warta, Cybina and Bogdanka rivers connecting city borders with the city centre.

In addition to the wedges, there are two green rings belonging to greenery system. The inner ring is running along the line of medieval city walls. The second ring is based on the remnants of the former Prussian fortifications of Poznan. The layout of this outstanding greenery system was developed by an architect and urban planner, Władysław Czarnecki, and a botanist, Adam Wodziczko in the years 1930–1934. The main purpose of the wedge system apart from providing recreational opportunities to residents was to ventilate the city and to protect surface waters. This extensive green network was meant to ensure internal coherence and spatial connectivity, enhance internal differentiation with the graduation of forms and functions of green areas and to establish connections with the natural environment beyond the borders of the city. The wedges form parks in the city centre, while in the outskirts of the city they integrate urban forests, allotment gardens, meadows and pastures.

Some fragments of this greenery system have been transformed into built-up areas, or are threatened by new investments, but the assumptions of this coherent system are still valid. Spatial planning documents of Poznan, including the land use plan mention green wedges and green rings as basic elements shaping the spatial structure of the city.

The wedges with open areas and greenery function as air corridors that improve air circulation by allowing air exchange in the city. As the wedges extend beyond city borders, they supply air from non-urban areas and through this effectively contribute to the dilution of pollutants in the inner city.



Sources:
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Dymek, et al. (2021)[98]
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http://cytadela.scienceontheweb.net/nature.html[100]
Image: City of Poznan

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