sustainability

MDPI

Review

Urban Vegetation in Air Quality Management: A Review and Policy Framework

Joanna Badach [1,*], Małgorzata Dymnicka [2] and Andrzej Baranowski [3]

1 Department of Urban Architecture and Waterscapes, Faculty of Architecture, Gdańsk University of Technology, 11/12 Narutowicza Street, 80-233 Gdańsk, Poland
2 Department of Urban Design and Regional Planning, Faculty of Architecture, Gdańsk University of Technology, 11/12 Narutowicza Street, 80-233 Gdańsk, Poland; mdym@pg.edu.pl
3 Department of Environmental Design, Faculty of Architecture, Gdańsk University of Technology, 11/12 Narutowicza Street, 80-233 Gdańsk, Poland; baranowskiandrzej1@gmail.com
* Correspondence: joanna.badach@pg.edu.pl

Received: 9 January 2020; Accepted: 6 February 2020; Published: 10 February 2020

check for updates

Abstract: Recent episodes of high air pollution concentration levels in many Polish cities indicate the urgent need for policy change and for the integration of various aspects of urban development into a common platform for local air quality management. In this article, the focus was placed on the prospects of improving urban air quality through proper design and protection of vegetation systems within local spatial planning strategies. Recent studies regarding the mitigation of air pollution by urban greenery due to deposition and aerodynamic effects were reviewed, with special attention given to the design guidelines resulting from these studies and their applicability in the process of urban planning. The conclusions drawn from the review were used to conduct three case studies: in Gdańsk, Warsaw, and Poznań, Poland. The existing local urban planning regulations for the management of urban greenery were critically evaluated in relation to the findings of the review. The results indicate that the current knowledge regarding the improvement of urban air quality by vegetation is not applied in the process of urban planning to a sufficient degree. Some recommendations for alternative provisions were discussed.

Keywords: pollution deposition; pollution dispersion; urban vegetation system; air quality management; urban planning

---

1. Introduction

Over one half of the world's population are now living in urban areas and in the European Union, the urban population ratio is expected to reach almost 0.75 [1,2]. The current degree of urbanisation results in increased pollution levels in cities due to human activity [3]. According to World Health Organisation experts, in 2016 alone several million cases of premature deaths were due to exposure to outdoor air pollution, the threshold concentration levels of which were significantly exceeded in many cities worldwide [4]. A recent study estimated that in Europe the average life expectancy is reduced by about 2.2 years due to exposure to air pollution [5]. Alongside many monitoring programmes and legal tools aimed at limiting pollution, the process of local spatial planning can offer some prospects for achieving environmental goals [6]. However, the current body of knowledge on the impact of the urban structure on air flow and pollution dispersion is still not sufficiently applied in urban planning and decision-making [7,8]. This also pertains to the development of the urban vegetation system. However, the association between urban vegetation and air quality is very complex and not easily evaluated or quantified.

The objective of this work was to explore the prospects of air quality improvement within local spatial planning strategies involving proper design and protection of urban vegetation. The most recently published works in which the relationship between urban vegetation and air pollution mitigation was investigated were reviewed, focusing on the practical implications of the reported results. The aim was to provide an up-to-date summary of the current state-of-the-art information to inform designers, urban planners, and policymakers on how to fully benefit from these findings. The most important guidelines for urban planning and design, indicated in the referenced studies, have been critically evaluated. The outcomes of the review were then used in an analysis of the existing provisions for the development and conservation of the urban vegetation systems in three Polish cities: Gdańsk, Warsaw, and Poznań. These three cities were selected because they exhibit heterogenic parameters in terms of their morphology, vegetation systems, and local planning provisions and hence can be used to illustrate the discussed issues. The analysis was also broadened by conducting a social study utilising free-form interviews with local experts involved in the process of urban planning and design as well as air quality management. Policy implications for the integration of urban vegetation management with air quality improvement and prospects for further research were also discussed. The proposed approach is presented in Figure 1.

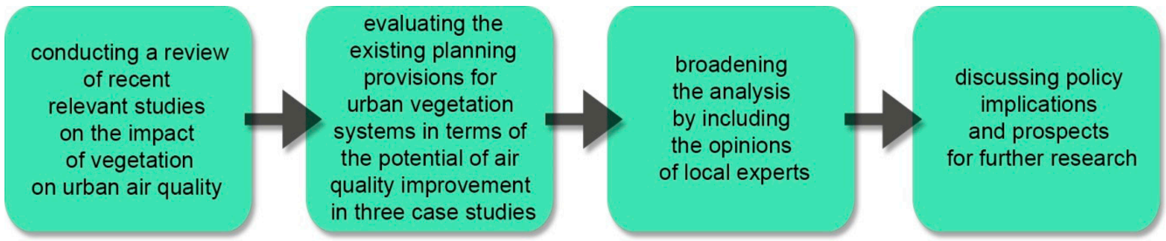


Figure 1. A scheme illustrating the outline of the article.

2. The Impact of Urban Greenery Systems on Urban Air Quality and Pollution Mitigation

Various effects of urban green infrastructure on air quality were considered in a wide range of studies. Given the rapid development and methodological complexity of this field, it is difficult for designers, urban planners, and policy makers to follow all the recent studies and fully benefit from their findings. The literature databases were queried using the following phrases: vegetation OR tree(s) AND air quality OR air pollution. The returned results were then filtered using pre-defined inclusion criteria. Only original research papers written in English and published in JCR-listed journals in the last five years were included. Moreover, we only considered studies in which design implications for the urban vegetation systems in terms of air quality improvement were emphasised. Two main effects of urban vegetation on air quality can be distinguished: the effect of the deposition of pollutants on plants and the aerodynamic effects of vegetation on air flow and pollution dispersion [9]. Therefore, the selected studies were divided into three main parts: (1) studies accounting for the removal of air pollution by vegetation due to the deposition effects, (2) studies considering the aerodynamic effects of vegetation, and (3) studies in which both processes were considered. Moreover, each part was further subdivided according to the applied urban scale. Finally, a wide variety of research methods included in the reviewed works were summarised. It is important to note that because in many cases the methods overlap between various categories, the method used for obtaining original data was used as a key factor.

2.1. The Deposition Effects of Urban Vegetation

Despite the availability of relatively accurate tools, estimating pollution removal by vegetation is a rather complex process in which numerous factors need to be included [10]. Therefore, this effect is still not fully understood, especially given the fact that the adsorption, deposition, or retention capacity of plants is affected by many factors such as leaf structure, tree height and canopy geometry, source location, and meteorological conditions [11,12]. Modelling and experimental results may differ between various studies. However, they might still provide some useful insights for the process of urban planning [13]. The research methods used in the reference studies are summarised in Table 1.

Table 1. A summary of research methods used in the referenced studies accounting for the deposition effects.

Method	Reference
Field Measurements and/or Laboratory Analysis	
On-site air quality measurements, also if coupled with field vegetation inventories, and data analysis	[14–30]
On-site air quality measurements or soil sampling, measurements of pollution removal by means of laboratory techniques, including instrumental analysis on plant samples (e.g., microscopic analysis, spectroscopy, gravimetry, gas exchange measurements, wind tunnel experiments on leaves or branches etc.) and data analysis	[31–35]
Measurements of pollution removal by means of laboratory techniques, including instrumental analysis on plant samples and data analysis	[11–13,36–59]
Estimates of pollution removal by vegetation or statistical analysis based on field plant inventories or remote sensing data and existing literature/databases or air quality data	[60–66]
Modelling Approaches	
Semi-empirical (operational) air quality models	
Air pollution tree removal model simulations	[10,67–73]
Online operational atmospheric chemical transport and dispersion model (ACTDM) coupled with mesoscale meteorological numerical weather prediction Regional Boundary Layer Model (RBLM) simulations	[74]
Numerical air quality models	
Computational fluid dynamics (CFD) simulations and on-site air quality measurements, or measurements of pollution deposition on plant samples using laboratory techniques or wind tunnel experiments	[75]
CFD simulations and dry deposition velocity model, combined three different wake turbulence models	[76]

Moreover, various scales were applied (see Table 2). The majority of recent studies investigating the efficiency of vegetation in air pollution removal were scaled to the plant level and the differences between species and their morphological features were investigated. At the micro-scale level, single elements of the geometry of the urban canopy layer were investigated, such as buildings or building complexes, street canyons, roads, or urban parks. In particular, vegetation around building complexes [15], near-road locations [14,19,21,23,24,26–28,34,75,76], urban green spaces [16,22,44,63], or green roofs [17,29] were considered. The studies at the neighbourhood scale, in which several urban blocks or large open urban areas were considered, or at the city scale, which included the area of the entire municipality, were less common.

Table 2. The scale of the studies accounting for the deposition effects in terms of the applicability of the results.

Scale	Reference
Plant level study	[10–13,31–33,35–43,45–59,65,69,73]
Local scale	[14–17,19,21–24,26–29,34,44,63,75,76]
Neighbourhood scale	[18,20,25,30,64,66,68,70]
City scale	[60–62,67,71,72,74]

2.1.1. Plant-Level Studies

In many plant-level studies, the air pollution removal effectiveness quantified e.g., as the pollution deposition rate, was established and significant differences between selected species that are common in particular areas were observed in many cases. For example, 2.5 to 6 times higher pollution removal capacity of the most effective trees in comparison to species with a minimum capacity was observed [11]. This indicates that particular species may be more suitable for a given area since air pollution mitigation is species-specific [54]. Therefore, many of the studies were concluded with some recommendations regarding the planting practices or with rankings of tree species for particular areas or climatic conditions. However, these results usually refer to a particular pollutant and they may be relevant only to the selected location, e.g., results obtained for samples collected in the Greater Sydney Region were not consistent with findings for Southeast Asian plant species [37]. Therefore, these results should be used with caution and their transferability to other urban areas should be subjected to re-evaluation in a specific environment [38].

Moreover, many other factors need to be taken into account in planting recommendations. For example, although deciduous species were identified as the most effective in accumulating and retaining airborne particulates in Mediterranean urban environments, including evergreen species was also recommended, especially given that higher particulate matter (PM) concentrations generally occur in winter [55]. This is because the majority of annual pollution accumulation occurs on leaf surfaces [42]. Another factor to consider is the species tolerance to air pollution. Similarly to air pollution removal efficiency, rankings of species with the highest air pollution tolerance can be made for selected species that are common in a particular area. Such rankings may result in planting recommendations in which both aspects are taken into account and for example, species with a high tolerance index and moderate dust removal can be identified [56,57].

In some studies, a strong dependency of the results on local conditions was shown. For example, for different wind conditions, the pollution retention capacity can vary, even 10-fold [46]. Temperature is also an important factor [33]. In some cases, the measured air pollution removal efficiency varied for different sampling months [36] or seasons [50] and for different distances from the emission source [43]. Given the above-mentioned aspects and the fact that the studies were restricted to species common in particular countries or geographical regions, their practical design implications are quite limited. However, some practical guidelines can also be found. Identifying the most effective species in air pollution removal may provide some useful suggestions for species alteration in proper urban vegetation management, which was confirmed by transferring the results of a plant-level study to a scenario modelling for the whole city [49]. However, accounting only for one parameter is a considerable simplification because the aerodynamic effects may also play a vital role in the deposition process [32]. Moreover, broader sampling campaigns at various times of the year would be useful to compare some seasonal differences and obtain more comprehensive results [39].

2.1.2. Local-Scale Studies

For local-scale studies, to date, the varying methodologies and habitats do not allow for meaningful comparisons [19]. Similarly to plant-scale studies, a variety of local conditions, such as meteorological factors, may have a significant impact on the results [23,24]. Although increasing the amount of urban greenery was found to be adversely associated with local air pollution concentration levels in various scenarios and it has been advocated as a mitigation strategy (e.g., [15,26,29,34]), other studies were less optimistic. For example, the effect of urban vegetation on air pollution removal was found to be negligible in northern European climatic conditions (for the investigated NO_2, O_3, and volatile organic compounds [VOCs] pollution) [21].Moreover, in another case, it was observed that only O_3 concentration levels were lower in tree-covered habitats than in open habitats, while there was no significant difference for NO_2 and SO_2 and total polycyclic aromatic hydrocarbon (PAHs) concentration levels were higher in tree-covered habitats, which may be partly explained by pollution trapping by the tree canopy [22]. Forests near major roads may slightly worsen air quality in terms of traffic-related NO_2 pollution, however for $PM_{2.5}$ pollution, no difference between open and vegetated areas was found and for coarse PM (>$PM_{2.5}$) and large PM (>PM_{10}), the air pollution concentration levels were lower in the forest than in open transects [19]. Finally, in one study, a significant decrease according to the distance from the traffic lane was observed for PM_{10},$PM_{2.5}$,and black carbon (BC) concentrations [24], while in another study, it was concluded that only a decrease in BC concentrations occurred with increased distance from the road and a similar effect was not observed for PM pollution [23].

Specific versatile guidelines for the vegetation design cannot be given because their capacity to remove pollutants may depend on wind conditions and may differ for various pollutants [27,28]. Satisfactory predictions obtained with the modelling approaches were reported in some cases, which was also validated with wind tunnel data [76]. However, in other cases, rather weak agreement between the modelled and measured in situ results was observed, which may be explained by the applied model parameters or inadequate estimation of emissions sources [75]. The size and density of green areas as well as the vegetation structure, composition, and management were selected as important parameters in air quality improvement [44,63]. Moreover, because altered PM_{10} concentrations in the vicinity of the crown were observed when a more detailed tree crown model was applied, it was also suggested that tree representations in 3D air quality models are usually overly simplified and using tree geometries obtained using light detection and ranging (LiDAR) techniques may constitute a valuable alternative [75].

Several design implications were discussed based on the conducted studies. For example, separating people from traffic to reduce exposure to pollution by applying road-side vegetation barriers or locating parks and recreational areas away from traffic can be generally advocated [26]. Various recommendations for the design of tree and hedge barriers were also given [14,27,28,34]. For example, in some scenarios near major freeways, PM pollution reduction was most effective for combination barriers consisting of both solid and vegetation elements [27]. Roadside barriers consisting of trees with gaps were found to be less effective than thick tree barriers with no gaps [34]. Finally, because non-uniform barriers may lead to lower pollution removal efficiency, not only their design but also their proper maintenance is very important [28].

2.1.3. Neighbourhood-Scale Studies

Studies in which pollution removal is estimated or modelled at the neighbourhood scale need to account for a variety of factors and local conditions and they often contain many uncertainties regarding the behaviour of air pollutants, so the results may differ depending on the site and the design of the study [25]. Estimates at the neighbourhood scale broaden the understanding of the processes of pollution removal and carbon storage and sequestration and provide recommendations for policy-making [66,68,70], however they are not easily transferable to other areas. For example, the coupled effects of vegetation and soil were identified as a pollution sink in Mexico but as a pollution source in Singapore [64]. Although trees generally have the highest pollution removal efficiency, the combined effects of various vegetation types, e.g., green roofs and green walls, can also be accounted for in modelling approaches. However, the scenarios with green roofs and walls may not provide significant improvements in air quality [68].

The number of studies investigating pollution removal by vegetation at the neighbourhood scale by means of measurements, rather than model estimates, is still too low [20,25]. Moreover, the results of these measurements are also often too inconclusive to be incorporated in the development of urban greenery solutions for air quality improvement. For example, in one study, the amount of green space was found to be negatively correlated with traffic-related particulate concentration levels, but no distinguishable trends were established in this scenario for gaseous pollutants [25]. In another study, O_3 concentration levels were significantly lower in areas with trees, but lower concentrations in these areas were not observed for NO_2 [20]. Similarly to estimates and modelling approaches, the statistical models based on on-site measurements also do not account for many factors. For example, because wind conditions have a major impact on air pollution concentration levels, the inclusion of wind data in such models would provide valuable insights [18]. On the other hand, some local policy implications can be obtained from such studies, such as the suggestion that the structure of green belts is most effective in particle pollution removal when it consists of different arrangements of tall and low vegetation rows [30].

2.1.4. City-Scale Studies

At the city scale, a statistically significant spatial relationship between urban forestry and air pollution mitigation was established [61]. Moreover, trees were observed to be more efficient in removing air pollutants than other types of vegetation, e.g., grass, and their efficiency varies between species [71,74]. Some of the reference studies resulted in estimates of annual pollution removal balance by the existing vegetation for selected pollutants, the results of which vary between the investigated sites or pollutants [60,62,71,72]. For example, municipal trees in Strasburg reduced the emitted PM_{10} by 7% due to the deposition effect [71]. The air pollution removal capacity of the existing urban forest was up to 5% for O_3 and 13% for PM_{10} in Florence [60]. A weaker effect of local air quality improvement in terms of $PM_{2.}$5of up to 3% and up to 1% on average due to the deposition effect of vegetation for the existing greenery scenario was estimated for Shenzen [72]. On the other hand, other studies were often performed only for a limited time period, which does not account for, for example, different meteorological conditions. Moreover, studying future scenarios consisting of various planting strategies might also bring some valuable insights [72,74].

Estimating the efficiency or the spatio-temporal gradient of air quality removal by vegetation both for the existing green infrastructure and for future scenarios provides support for urban forest management at the municipal scale [67,71,72]. Moreover, it can also be used to create planting schemes by ranking high- and low-priority areas and to reconcile the issue of air quality improvement with other ecosystem services [67]. On the other hand, it requires large amounts of input data, such as remote sensing data on land cover, air quality data from local monitoring stations, geospatial data, etc. [72]. Therefore, its practical applicability is limited.

2.2. The Aerodynamic Effects of Urban Vegetation

The majority of studies investigating the aerodynamic effects of urban vegetation pertained to the local scale and in the remaining studies, the neighbourhood scale was applied. Computational fluid dynamics (CFD) is most commonly used to investigate the aerodynamic effects of vegetation because it cannot be included in various models simulating urban-atmospheric interactions at the mesoscale [77]. This is because the capacity of CFD to solve internal and external flows has improved significantly in recent decades [78], leading to its increasing use in a number of fields, including urban air quality modelling. The majority of the studies performed by means of CFD were limited to local domains such as isolated street canyons, near-road arrangements, or building blocks and building clusters. This is because they still require not only considerable computational resources, but also detailed traffic models, urban tree parameter datasets, and a more representative air quality monitoring network to obtain more comprehensive input data [79]. However, some CFD studies at larger urban scales have been performed recently, as illustrated by several referenced neighbourhood-scale studies. Regardless of the scale, CFD simulations still have considerable limitations because due to computational demands, the full scope of real-life parameters cannot be applied and some assumptions have to be made according to the specific purpose of each study [80]. In some studies, wind tunnel experiments, on-site air quality measurements, other numerical models, and semi-empirical air quality models were also applied. The chemical reactions and dry deposition effect tended to be ignored, given the short time scale considered [81]. The research methods are summarised in Table 3.

Table 3. A summary of research methods used in the referenced studies accounting for the aerodynamic effects.

Method	Reference
Field Measurements and/or Laboratory Analysis	
On-site air quality measurements, also if coupled with field vegetation inventories, and data analysis	[82]
Wind tunnel experiments on physical models of urban geometries	[83]
Modelling Approaches	
Semi-empirical (operational) air quality models	
Dispersion model based on the gradient transport theory and on-site air quality measurements	[81]
Urban canopy model simulations	[84]
Numerical air quality models	
Computational fluid dynamics (CFD) simulations with established, previously validated models or models validated against data from previous studies or existing databases	[9,77,79,85–91]
CFD simulations and on-site air quality measurements, or measurements of pollution deposition on plant samples using laboratory techniques or wind tunnel experiments	[78,92,93]
CFD simulations coupled with photochemical equations for NO_X, and O_3 transport	[94]
Coupled CFD-Lagrangian stochastic model (CFD-LSM) simulations	[95]
Parallelized Large-Eddy Simulation Model (PALM) with embedded Lagrangian stochastic particle model (LPM) simulations	[96]

In the studies accounting for the aerodynamic effects, the local or neighbourhood scale was applied (see Table 4). At the local scale, street canyons were mainly investigated, using either idealised 2D [78,92] or 3D street canyon geometries [83,85,89,90,95] or more realistic street canyon models based on existing geometries [93]. Idealised urban blocks, consisting of an array of buildings with several street canyons [87,88,94], were also used as a computational domain. There was also a single case of a realistic 3D scanned single-tree model placed in a street canyon geometry [91]. Some of the studies were also focused on near-road arrangements [81,86]. At the neighbourhood scale, larger computational or experimental domains of up to a couple of square kilometres were applied. In numerical simulations, detailed 3D models were used [9,96], including 3D models based on LIDAR measurement data [77,79]. At both the local and neighbourhood scales, vegetation was modelled as a porous medium with simplified geometry and/or its effect was parameterised.

Table 4. The scale of the studies accounting for the deposition effects in terms of the applicability of the results.

Scale	Reference
Local scale	[78,81,83,85–95]
Neighbourhood scale	[9,77,79,82,84,96]

2.2.1. Local-Scale Studies

Although air flow characteristics at the urban micro-scale, for example, in street canyons, are dominated by wind direction and canyon geometry, the effect of vegetation is not negligible [78,87–89]. Some of the studies reported an overall improvement of air quality and reduced air pollution concentration levels due to the effects of vegetation for some wind conditions and vegetation scenarios [83]. Moreover, street trees, also combined with other barriers such as parked cars, were suggested as a strategy to reduce pedestrian exposure to traffic-related pollution [85]. On the other hand, in many cases, increased air pollution concentration levels due to decreased air flow velocity and turbulence intensity caused by street canyon vegetation was observed [78]. Moreover, while a moderate overall increase in pollution concentration levels was observed in some cases, at the same time, very strong local decreases or increases in concentration levels occurred [87,88].

The above-described effects depended on many factors, one of which was the applied wind direction, with different results observed for winds parallel or perpendicular to the street canyon geometry [83,92,93,95]. Another factor was the structure of vegetation, including its geometry, height, and porosity [91,95]. For example, in a broad street canyon geometry, an overall improvement was obtained for dense trees, suggesting that in such a case, they might serve as a mitigation strategy, while for sparse and tall trees in the same geometric conditions, a pollution trapping effect was observed [95]. Moreover, for the same tree volume and trunk height, it was observed that tree arrangement had very little influence on flow structure and concentration distribution and the trunk height was the most important factor influencing the air flow and pollution dispersion [89]. Finally, the aerodynamic effects of trees in street canyons may depend on the geometry of the canyon itself. For example, it was reported that in square street canyons, trees generally deteriorated ventilation and pollution dispersion, but the strongest trapping effect was discovered for barrow-shaped canyons [95].

Two open-area near-road scenarios were also considered [81,86]. Similarly to some street canyon results, it was suggested that dense vegetation barriers in near-road locations can act similarly to solid barriers because they induce an updraft motion of pollution, leading to decreased air pollution concentration levels through vertical mixing. On the other hand, porous barriers lead to higher air pollution concentration levels because they reduce wind speed. Therefore, the results of the studies investigating the correlation between local air pollution concentration levels and leaf area density (LAD) of near-road vegetation barriers can be used to optimise their design [86]. Moreover, applying a distance of 17m from the emission source (road) was proposed for urban parks because it was established that such a distance, under typical urban conditions, constitutes a halving distance for air pollution concentration level decrease and can serve as a buffer zone [81].

Although it was suggested that the results of the studies may be used by urban planners in urban planting scenarios [86,89,94], or in locating urban green spaces [81], the reported results depend too strongly on the study design and applied boundary conditions. Moreover, many other local effects, such as pollution deposition, emission of VOCs by trees, or vehicle wakes, were not considered in the presented studies [85,95]. Similarly, the heat trapping mechanism of trees is not accounted for in the majority of the studies, which can lead to underestimation of the near-ground air pollution concentration levels [93]. However, investigating the impact of the infrastructural and vegetation design on local air flow is very important and may provide valuable suggestions for a particular case study, for example, regarding the most advantageous vegetation scenario for prevalent local winds [85,92]. Therefore, although general guidelines cannot be given, each design case should be considered carefully and preceded by local air flow studies. Finally, combining local and neighbourhood scale air flow studies was advocated for design decisions [87,88], as well as applying a broader scope of meteorological conditions [94]. In a recent study, it was also suggested that in order to obtain more accurate results, realistic tree geometries should be used [91], however due to high computational costs, in the majority of studies, simplified vegetation models were used.

2.2.2. Neighbourhood-Scale Studies

At the neighbourhood scale, it was observed that traffic-related air pollution concentration levels increased in street canyons but decreased in open-terrain configurations, with an overall decrease at pedestrian height by 7% on average. These results indicate that local solutions for tree planting should be integrated with regional-scale planning because in some local-scale studies, a negative impact of vegetation on pollution dispersion was suggested [79]. On the other hand, for perpendicular wind direction, similar to the prevailing wind in the investigated area, increased LAD was observed to decrease wind speeds and thus increase in the average air pollution concentration levels at the neighbourhood scale [9]. Similarly, according to another study, an increased green coverage ratio decreased the wind velocity ratio [84]. It was also indicated that street trees alter the flow field and canyon vortex and hence reduce the efficiency of ventilation related to pollution dispersion [96]. Finally, trees planted in the proximity of major roads can increase local air pollution concentration levels downwind [82]. The degree to which trees influence the urban wind environment depends largely on the urban density or the density and typology of the urban canopy, which is strongest in waterfront and low-density areas [84]. Moreover, local prevalent wind direction is also an important factor [82]. This indicates the need to develop street tree-planting scenarios based on predictions of their effects on ventilation, taking into account various factors such as locally occurring emissions [9].

Although CFD studies at larger urban scales are becoming increasingly available, they require detailed emission data, urban tree parameter datasets, and representative air quality monitoring networks to obtain more comprehensive input data [79]. Therefore, CFD or wind tunnel studies are still limited mainly to research because they are time- and labour-intensive [84]. Moreover, it is still quite rare to investigate various real urban design scenarios, including the landform and the urban canopy model at the neighbourhood scale, to choose the best design solution for urban geometries and vegetation in terms of air quality improvement. Therefore, some semi-empirical dispersion models with practical application were also sought. For example, a model that correlates tree geometry indices with wind speed can easily be used by urban planners to control the density and the parameters of the urban canopy, for example, by properly arranging or choosing certain species to improve air quality [84].

2.3. Coupled Deposition and Aerodynamic Effects of Vegetation

In the previous paragraphs, studies that account for either aerodynamic or deposition effects of urban vegetation were summarised. However, taking into account both processes to obtain a comprehensive assessment is potentially more useful for urban planning [97]. For example, when the deposition effect is not considered, the results might suggest that street vegetation leads to increased air pollution concentration levels by reducing ventilation efficiency. Therefore, including deposition might be necessary to obtain a comprehensive picture [98]. On the other hand, some plants are characterised by very high pollution removal efficiencies, which may be underestimated in CFD studies, so more updated data on the removal rates by leaf deposition data are needed [45]. The research methods are summarised in Table 5.

Table 5. A summary of research methods used in the referenced studies accounting for the coupled deposition and aerodynamic effects.

Method	Reference
Field Measurements and/or Laboratory Analysis	
On-site air quality measurements, also if coupled with field vegetation inventories, and data analysis	[99]
On-site air quality measurements or soil sampling, measurements of pollution removal by means of laboratory techniques, including instrumental analysis on plant samples and data analysis	[100]
Modelling Approaches	
Numerical air quality models	
Computational fluid dynamics (CFD) simulations with established, previously validated models or models validated against data from previous studies or existing databases	[80,97,98,101–109]
CFD simulations and on-site air quality measurements, or measurements of pollution deposition on plant samples using laboratory techniques or wind tunnel experiments	[110–112]
CFD simulations and drift flux model simulations	[113]
CFD simulations and drift flux model simulations and on-site air quality measurements	[114,115]
Mesoscale Weather Research and Forecasting (WRF) model simulations and CFD simulations	[116]
Mesoscale WRF model coupled with chemistry (WRF-Chem) and Building Effect Parameterization (BEP) simulations	[117]

At the local scale street canyons, including street canyon trees [101,104,105,109,113,114] and green walls and roofs [115], near-road vegetation [102,108,110,111] and urban green spaces [98,106,112] were investigated. In 3D simulations idealised models [101,105,106,109–115] or more complex 3D models based on existing geometries [104] were used with vegetation modelled as a porous medium with simplified geometry. For roadside barrier arrangements, their different configurations and characteristics, such as porosity, gaps, or thickness, were considered [102,108]. In the studies, a neighbourhood scale of up to several square kilometres was applied. In all of them, a more detailed 3D representation of existing geometries was applied [80,97,103,107,116]. Very few studies accounting for both the deposition and aerodynamic effects were performed at the city scale. For references, see Table 6.

Table 6. The scale of the studies accounting for the deposition effects in terms of the applicability of the results.

Scale	Reference
Local scale	[98,101,102,104–106,108–115]
Neighbourhood scale	[80,97,103,107,116]
City scale	[99,100,117]

2.3.1. Local-Scale Studies

In the case of street canyons, an annual average increase in air pollution concentration levels by about 8% for elemental carbon and an increase of about 1.4% for PM_{10} due to the effects of trees was reported [109]. In other cases, it was observed that street canyon trees generally led to an increase in air pollution concentration levels due to the obstruction of flow [101,113]. In some of the studies, it was also emphasised that the deposition effect was too small to effectively remove the pollutants trapped in street canyons [101,113]. On the other hand, according to other results, air pollution concentration levels were lower at the pedestrian level for the tree scenarios [105]. In the case of green walls and green roofs in street canyons, it was observed that they improved air quality at the pedestrian level in terms of PM pollution [115]. Wind direction—resulting from the orientation of the street canyon, tree configuration, crown morphology, and canopy porosity—were identified as important factors in the processes described above [101,105,109,114].

In the case of near-road arrangements, different parameters of vegetation barriers were investigated. Both hedge and tree barriers were found to be effective in locally reducing near-road air pollution concentration levels in open road conditions, but trees are more crucial in this process [111]. Wide vegetation barriers with high LAD and vegetation–solid barrier combinations were most effective in traffic-related pollution mitigation [102,108]. Apart from vegetation barriers, near-road uniform-type green spaces were found to be less effective in PM removal, while more complex forms were more effective. Moreover, the purifying effectiveness varied for different species compositions [110]. Finally, urban green spaces were investigated. It was revealed that small-scale parks (less than 100m), even with very dense vegetation, do not cause substantial pollution removal due to the deposition effect [112]. It was also observed that in scenarios with trees and shrubs, the wind speed is lower in comparison to the non-green and grass scenario due to the effects of blocking; however, in tree scenarios, ventilation can be enhanced by appropriate and less compact arrangement of trees [106].

Similarly to studies accounting only for the aerodynamic effect of vegetation, general guidelines cannot be given. The model-based design recommendations, made based on isolated, generic configurations, may not account for the site-specific conditions [102]. For example, the results obtained for a road with a vegetation barrier on one side cannot be extrapolated for a street or avenue with vegetation on both sides because different design scenarios and conditions require individual case studies [111]. Other limitations are related to the currently most advanced and most commonly applied CFD approach because it cannot fully account for complex variations in wind strength and direction, dynamic chemical reactions, or for the effect of traffic turbulence on pollution dispersion [104]. Limited computational domain and types of vegetation can also be indicated [108]. Finally, the effects of greenery should not be investigated as an isolated process [113]. Some particular recommendations can also be found. For example, various structures of road-side green spaces can be used for different road and pavement configurations to reduce exposure to PM pollution [110]. The dominance of the aerodynamic effects of vegetation, as suggested in some studies, may indicate that increased air pollution concentration levels occur, for example, along park boundaries, so placing sports or recreational facilities away from park borders may be used as a strategy to limit exposure of park users to air pollution [112]. On the other hand, in another case, it was suggested that the deposition effect can counterbalance the increase in air pollution concentration levels caused by the dispersion effect in certain wind and tree scenarios [105]. It is also important to note that both economic and environmental perspectives should be taken into account in policy recommendations. For example, although the reductions of road-side NO_2 concentration levels due to the effect of trees were very small in comparison to those achieved with solid barriers, trees were still suggested as the most cost-effective mitigation strategy [104].

2.3.2. Neighbourhood-Scale Studies

Different local aerodynamic effects were discovered, such as an increase in traffic-related air pollution concentration levels in street canyons and along roadsides but a decrease in concentration levels in open terrain. However, when it comes to regional effects, the total aerodynamic dispersion induced by trees led to an 8% to 11% decrease in air pollution concentration levels, depending on the wind speed. In the same study, it was established that pollution deposition on vegetation is very limited locally [103]. Generally, the aerodynamic effects were found to be more significant than the deposition effects, even up to several times [97,103,107]. In other studies for street trees, decreased air pollution concentration levels and improved pollutant removal over the roofs of buildings in the case of parallel winds were discovered [80,97]. On the other hand, it was suggested that although adding more vegetation to the existing scenario would lead to a reduction in air pollution concentration levels, locally some pollution hotspots would appear. According to another study, adding green roofs had a negative effect on air quality, which was inconsistent with some previous studies [116].

The neighbourhood computational domain is rather rare for CFD simulations, the majority of which are restricted to local-scale geometries, because very high computational resources are required. Therefore, only very limited wind and vegetation scenarios can be investigated at such a scale [103]. It is even rarer to include different urban design and vegetation scenarios at the neighbourhood computational domain. However, such studies would provide more holistic insights into air pollution mitigation by green space planning [116], especially given the importance of the local wind conditions on this process [97,116]. Moreover, a strong link between the effect of trees on ventilation and the local scale was revealed [80]. Due to the limited number of neighbourhood-scale studies, even fewer general conclusions can be drawn. The coupled aerodynamic and deposition effects should be evaluated individually for every tree-planting scenario, especially because planting new trees affects air quality not only in the particular location but also around it [107].

2.3.3. City-Scale Studies

It was observed that pollution removal capacity does not only depend on the species; wind field is also an important factor affecting the process of deposition. Moreover, species selection is less effective than the appropriate arrangement of plants in mitigating air pollution, so it is important to study local wind conditions to optimise the efficiency of pollution removal by vegetation [100]. Interestingly, it was reported that in the case of some pollutants, concentration levels increase after implementing more greenery. This may be explained by the fact that vegetation reduces temperatures near the ground, leading to reduced turbulent exchange and decreased pollution dispersion efficiency. However, for other pollutants, reductions in concentration levels were observed. Therefore, the general conclusion was that the observed effects were too complex to propose any planning recommendations and because such case studies provide information only for a certain context, separate studies are needed for areas characterised by different meteorological and morphological conditions [117]. Finally, it was suggested that developing decision support tools for optimal greenery arrangements in terms of air quality improvement, which would take into account aspects such as budget and topographical limitations, is also necessary. Therefore, an agent-based model was proposed for this purpose, which was used to develop a tree-planting scenario allowing the limitation of local emissions and reduction of human exposure to pollution to the greatest possible extent with the available local resources [99].

3. Evaluation of Urban Planning Regulations in Gdańsk, Warsaw, and Poznań Concerning the Impact of Urban Vegetation on Air Quality

Local planning instruments are associated with the capacity to address environmental issues in a flexible, area-oriented approach [118] and for setting environmental objectives according to local conditions and functions. Therefore, novel decision-support tools for urban planners and policy makers, based on the available state-of-the-art methods and scientific procedures, are needed to improve urban ventilation and pollution dispersion [119]. The results of the reviewed studies can be used during the formulation of local spatial development guidelines to improve urban air quality. However, the possibility of their application in urban planning requires further research in which the local ecological or legal conditions are also considered. Therefore, three case studies were conducted in order to explore and highlight the applicability of research implications within the planning and spatial development systems in Polish cities.

Gdańsk (54.35° N, 18.65° E), a city on the Baltic coast and the largest in the Pomeranian Voivodeship, contains the largest Polish seaport. It covers an area of approximately 262 km^2 with a population of over 460,000. In terms of air quality, the geographical location of Gdańsk makes it a very interesting area for air quality investigation. On the one hand, it is located by the Gulf of Gdańsk, which facilitates air circulation; on the other, it is limited from the west and south by a moraine plateau [120]. The system of green areas in Gdansk is depicted in Figure 2.

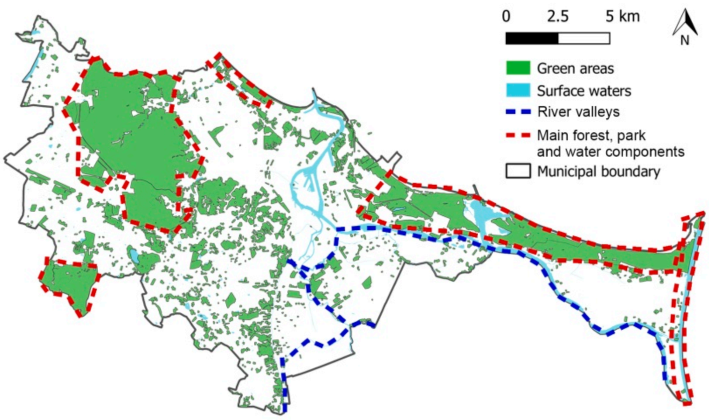


Figure 2. A scheme of the municipal system of biologically active areas in the Gdańsk. Map based on: [120].

Warsaw (52.2297° N, 21.0122° E), a city on the Vistula river, is the capital city and the largest city in Poland. It covers an area of approximately 517 km^2 with a population of over 1,770,000. Its spatial structure is defined mainly by the Vistula river valley and the Warsaw Escarpment. Moreover, there is a system of ventilation corridors (wedges), which cuts into the densely built-up areas [121]—see Figure 3. However, it is estimated that the efficiency of these corridors is varied and has decreased in recent years due to new developments within the corridors as well as deteriorating local ventilation conditions [122].

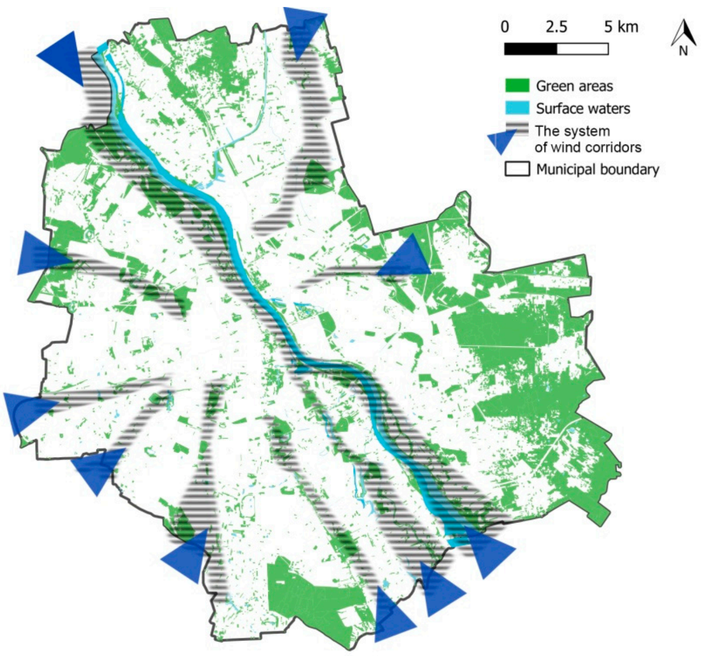


Figure 3. Scheme of the biologically active areas and the air exchange and regeneration corridors (marked in purple) in Warsaw. Map based on: [122].

Poznań (52.41° N, 16.92° E), a city on the Warta river in west-central Poland and the largest in the Greater Poland Voivodeship, is the fifth largest city in Poland. It covers an area of approximately 262 km^2 with a population of over 550,000. Its spatial structure is strongly formed by river valleys of the Warta, Bogdanka, and Cybina cutting into the city in the east-west and north-south directions [123]. Poznań is characterised by a very distinctive system of urban greenery—a system of green wedges and rings (see Figure 4).

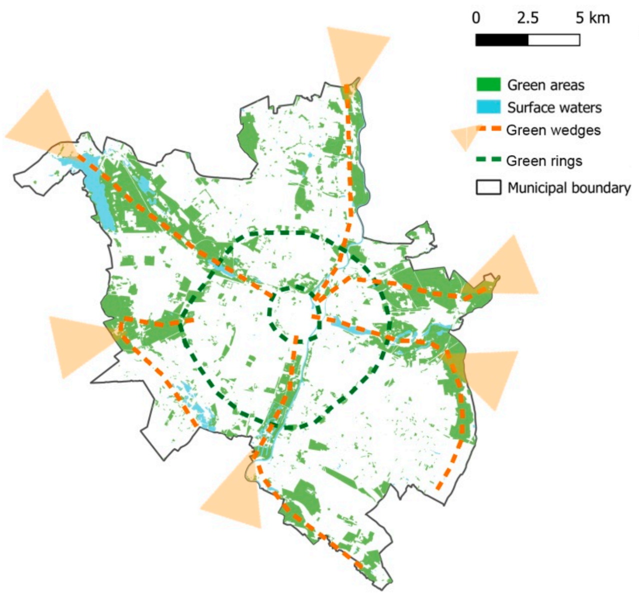


Figure 4. Scheme of the green wedges and rings greenery system in Poznań. Map based on: [123].

Within the planning system in Poland, local urban planning and design is based on the Local Spatial Development Plans (LSDPs)—municipal documents that are the grounds for administrative decisions regarding land use management and proposed new building projects [124]. Within the analysis of the existing planning regulations in the study areas, LSDPs were used in terms of the measures for the development and conservation of the urban greenery system. In the initial stage of the analysis, all the existing LSDPs were briefly studied. However, due to the considerable amount of planning documents and the repeatability of their provisions, it was decided to choose sample districts (planning units) in each city to narrow down the scope of the analysis. The sample districts were chosen as representative of the spatial structure of Polish cities, also referred to as the post-socialist city structure, which is typical for Central and Eastern Europe [125,126]. The following typologies were selected: (1) high-density historic centre with a medieval core, (2) low-density pre-war residential and commercial districts, (3) transition zone, consisting of both pre-war tenement houses and post-war socialist buildings, (4) post-war slab block housing estates, (5) predominantly low-rise mixed-function suburban zone, and (6) recently developed residential and commercial sub-centres. For each typology, existing districts from the three cities were included in the analysis. It should be noted, however, that in all cases, a clear division in the selected cities is not possible because some of the districts may have some elements of more than one typology. In such cases, the choice was based on the predominant typology.

The basic information about the selected districts is shown in Table 7, including $\mathbf{T_{SA}}$**:** the total site area, $\mathbf{P_{AD}}$**:** the plan area density (the fraction of site area covered by buildings), $\mathbf{A_{H}}$**:** the average height of buildings (weighted by building plan areas), and $\mathbf{G_{C}}$**:** the green coverage (the fraction of site covered by greenery—high greenery, low greenery, and agricultural areas, excluding grassy areas). The indicators were also calculated for the entire municipalities, for reference. The calculations were performed in QGIS V. 3.6.0 based on geospatial datasets provided by the Head Office of Geodesy and Cartography. The representation of the spatial structure of the urban districts was based on Google Earth images. Finally, 116 LSDP were considered for Gdańsk, 28 for Warsaw, and 23 for Poznań. The difference in the number of plans resulted from the unequal coverage of the municipal areas by the LSDPs and the different degree of planning system fragmentation between the three cities. Subsequently, the provisions for the development and conservation of the greenery system for these districts were extracted from the LSDP, as listed in Table 8. Recommendations were then developed to improve the existing provisions with regard to the current state-of-the-art in the field. The implementation of these recommendations within the planning documents would result in a more science-based development of the urban greenery system aimed at air quality improvement.

Table 7. The districts selected for the analysis of the local spatial planning provisions and their metrics: total area ($\mathbf{T_{SA}}$), plan area density—the proportion between the area covered by buildings and the total area ($\mathbf{P_{AD}}$), average buildings height (the number of levels) ($\mathbf{A_H}$), and greenery cover ($\mathbf{G_C}$).

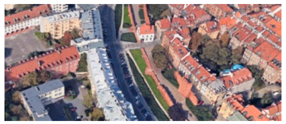
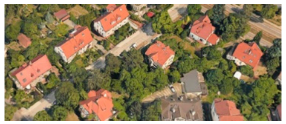
	Gdańsk $\mathbf{T_{SA}}$: 261.6 km^2, $\mathbf{P_{AD}}$: 4.5%, $\mathbf{A_H}$: 2.67 levels, $\mathbf{G_C}$: 27.2%	**Warsaw** $\mathbf{T_{SA}}$: 517.2 km^2, $\mathbf{P_{AD}}$: 8.3%, $\mathbf{A_H}$: 3.42 levels, $\mathbf{G_C}$: 25.4%	**Poznań** $\mathbf{T_{SA}}$: 261.9 km^2, $\mathbf{P_{AD}}$: 6.6%, $\mathbf{A_H}$: 2.61 levels, $\mathbf{G_C}$: 23.3%
			
1. High-Density Historic Inner City	**G1.** Main and Old Town, Old Suburb, and Granaries Island $\mathbf{T_{SA}}$: 2.5 km^2 $\mathbf{P_{AD}}$: 18.8% $\mathbf{A_H}$: 3.6 levels $\mathbf{G_C}$: 0.6% 	**W1**. Śródmieście (north of Świętokrzyska street) $\mathbf{T_{SA}}$: 5.7 km^2 $\mathbf{P_{AD}}$: 19.0% $\mathbf{A_H}$: 5.0 levels $\mathbf{G_C}$: 8.9% 	**P1.** Old Town $\mathbf{T_{SA}}$: 4.7 km^2 $\mathbf{P_{AD}}$: 20.1% $\mathbf{A_H}$: 4.4 levels $\mathbf{G_C}$: 14.6% 
2. Medium-Density Historic Neighbourhood	**G2. Upper** Oliwa (including universities and park areas) $\mathbf{T_{SA}}$: 5.2 km^2 $\mathbf{P_{AD}}$: 11.0% $\mathbf{A_H}$: 2.7 levels $\mathbf{G_C}$: 20.6% 	**W2.**Wierzbno (including park areas) $\mathbf{T_{SA}}$: 5.9 km^2 $\mathbf{P_{AD}}$: 6.3% $\mathbf{A_H}$: 4.1 levels $\mathbf{G_C}$:14.0% 	**P2.** Sołacz and Golęcin (including the park areas) $\mathbf{T_{SA}}$: 6.6 km^2 $\mathbf{P_{AD}}$: 4.8% $\mathbf{A_H}$: 2.0 levels $\mathbf{G_C}$: 43.8% 

Table 7. *Cont.*

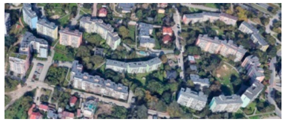
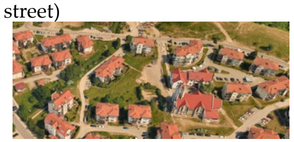
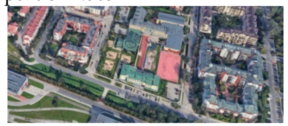
3. Transition Zone	**G3.** The area of Nowe Ogrody street (adjacent to the Main Town) **T_{SA}:** 1.4 km^2 **P_{AD}**: 8.6% **A_H**: 3.0 levels **G_C**: 29.9% 	**W3.** Śródmieście (south of Świętokrzyska street) **T_{SA}**: 3.0 km^2 **P_{AD}**: 44.6% **A_H**: 5.8 levels **G_C**: 17.7% 	**P3**. Łazarz **T_{SA}**: 3.4 km^2 **P_{AD}**: 23.9% **A_H**: 3.4 levels **G_C**: 4.1% 
4. Post-War Housing Estate	**G4.** Zaspa housing estate **T_{SA}**: 3.2 km^2 **A_H**: 8.6% **A_H**: 5.7 levels **G_C**: 7.6% 	**W4.** Warzyszew, Chomiczówka **T_{SA}**: 2.7 km^2 **P_{AD}**: 10.7% **A_H**: 6.3 levels **G_C**: 44.3% 	**P4.** Winogrady housing estate **T_{SA}:** 4.1 km^2 **P_{AD}**: 11.9% **A_H**: 4.1 levels **G_C**: 5.8% 
5. Low-Density Suburban Zone	**G5.** Orunia (north of the railway line) **T_{SA}**: 4.5 km^2 **P_{AD}**: 6.5% **A_H**:1.8 levels **G_C**: 10.3% 	**W5.** Falenica **T_{SA}**: 6.5 km^2 **P_{AD}**: 7.5% **A_H**: 1.8 levels **G_C**: 32.4% 	**P5**. Szczepanikowo, Spławie, and Krzesinki **T_{SA}**: 7.0 km^2 **P_{AD}**: 6.5% **A_H**: 1.6 levels **G_C**: 2.8% 
6. New Urban Sub-Centre	**G6.** Jasień Szadółki (between the railway line and Jabłoniowa street) **T_{SA}**: 3.8 km^2 **P_{AD}**: 5.1% **A_H**: 2.6 levels **G_C**: 27.0% 	**W6.** Kabaty and part of Natolin **T_{SA}**: 3.2 km^2 **P_{AD}**: 15.1% **A_H**: 4.2 levels **G_C**: 9.8% 	**P6.** Strzeszyn **T_{SA}**: 3.5 km^2 **P_{AD}**: 6.3% **A_H**: 2.4 levels **G_C**: 21.9% 

Table 8. Local Spatial Development Plans (LSPDs) provisions regarding urban vegetation and recommendations for air quality improvement.

Existing Provisions in Spatial Planning Acts: (A)—LSPDs for Gdańsk [127], (B)—LSPDs for Warsaw [128], (C)—LSPDs for Poznań [129]	Recommendations Based on the Conducted Review
- Formulating the minimum Ratio of Biologically Vital Areas (RBVA) for new building projects(the ratio between the areas covered by vegetation or open water and the plot size [130]) from 1% up to as much as100% of the plot, depending on the location and urban function (A, B, C) - Sometimes the minimum biologically vital area is also defined per 1m^2 of residential space (especially in residential areas), or it is required that all undeveloped parts of the plot be dedicated for biologically vital areas (especially in inner-city areas) (A, C) - For some inner city residential or commercial developments, RBVA is not defined (A, B, C)	- There are no provisions regarding the location of the recreational green areas in order to limit human exposure to air pollution (e.g., to avoid locating recreational green areas in the proximity of roads)
- Very rarely, more specific provisions regarding the structure of biologically vital areas are given, e.g., it is stated that they should consist of both low and tall greenery or that shrub and tree planting are required for a certain fraction of the biologically vital areas (e.g., 15–40%) (A, C)	- The commonly applied RBVA does not specify surface types, forms of vegetation, or their composition [124], which may result in planting only vegetation that is less effective in pollution removal
- Protection of existing greenery, especially trees with high landscape and natural values, and if cutting down existing trees is permitted, planting new trees is usually required (A, B, C) - Sometimes the protection of the existing greenery is also specified within separate provisions for existing ecosystems, e.g., the Municipal System of Biologically Active Areas and the Tri-City Landscape Park in Gdańsk (A), the Kabacki forest in Warsaw (B), or the system of municipal fortifications and "Nature 2000" areas in Poznań (C)	- Protection of existing green areas is very important for urban air quality improvement - The provisions regarding the biologically vital areas for each site donot refer to the area of the entire municipality—estimates at a larger scale are needed
- Planting vegetation barriers, especially consisting of tall vegetation, is often required along roads and around car parking areas (A, B, C) - Sometimes the vegetation barriers are only defined as a row of tall vegetation (A, B, C) and less frequently, more specific guidelines are given, for example, their width and height are defined (A)	- Planting new trees should be preceded by air flow studies taking into account local conditions. These studies are especially important for certain locations such as street canyons or along roads, where the effect of pollution trapping due to the presence of vegetation may lead to increased pedestrian exposure
- Sometimes planting of vegetation barriers is also proposed along watercourses (A, C), e.g., as a row of trees or as green belts, with no guidelines or only some guidelines regarding its structure given (e.g., the minimum width) (A)	- Planting tall vegetation along watercourses may impede ventilation, in which the waterfront areas play a crucial role [131], so it should be preceded by air flow studies
- Sometimes planting tall greenery is restricted in some inner city areas, also in order to prevent blocking the exposition of important historical landmarks (A,C)	- The limitations in planting tall greenery should also be based on air flow studies, not only on aesthetic reasons
- In most cases, no provisions regarding the choice of species are given (A, B, C) - Sometimes it is stated that species should be chosen that are typical for a particular ecosystem(A) or characterised by high aesthetic qualities or good resistance to local climatic and meteorological conditions (A, C) - In some cases, it is also suggested that the selected species should be characterised by good resistance to air pollution, e.g., traffic-related (A)	- Detailed studies are needed for the species common to the study areas in terms of their pollution removal efficiency to provide guidelines for future planting

4. Further Implications for the Current Practice of Urban Planning and Policy-Making in Poland

The ecosystem services of urban vegetation still require greater recognition, despite the growing body of evidence [71]. In order to broaden the study, a group of local experts consisting of the representatives of the local authority, academics, architects, and urban activists were interviewed to obtain more information about the prospects of air quality improvement within the investigated planning systems. The respondents were chosen in such a way that the variety and complexity of the discussed problems could be explored. Moreover, only these experts were included, who had a sufficient understanding of and experience in the issue of urban air quality management or integrated urban and environmental planning and design. This allowed us to collect experts' opinions and remarks, which may indicate new approaches towards urban air quality mitigation within the practice of urban planning and vegetation management, help to critically evaluate the existing standard procedures, and, finally, outline prospects for further research and policy directions. This research approach also allowed us to show the social aspect of the issue.

The free-form interviews were conducted in spring 2019. Only experts from Gdańsk were included, however their statements referred to Polish urban planning and air quality monitoring systems in general, so it can be assumed that they are also representative of other Polish cities. The experts were questioned about a wide variety of issues related to the impact of urban planning on air quality improvement, including the following aspects:

1. the current status of urban air quality in Poland;
2. the presence of the issue of urban air pollution in public debate;
3. the importance of social participation in the process of air quality improvement;
4. the cooperation between local stakeholders (institutions, organisations, and residents) in terms of urban air pollution mitigation;
5. the existing urban planning tools aimed at air quality improvement;
6. the future directions of urban development.

From all the conducted interviews (10), only statements that pertained to the system of urban planning and vegetation management were selected. The opinions of the following experts were presented:

(X) a representative of the local air quality monitoring agency;
(XI) a local activist, a representative of a local urban movement;
(XII) an academic;
(XIII) a representative of the municipal department of vegetation and road infrastructure management;
(XIV) an architect and a representative of a local ecological organisation;
(XV) owners of an architectural design studio;
(XVI) a representative of the municipal department of the environment;
(XVII) a local activist and a representative of a district authority.

In many cases, the interviewed experts pointed out the issues that were also discussed in the reviewed studies. According to the first expert, in many Polish cities, there is a lack of comprehensive analyses of pollution removal by the urban vegetation system at the municipal scale. If such analyses were conducted, they would be helpful in formulating long-term policies for spatial development and conservation of the vegetation system (X). Such a recommendation was also included in some of the reviewed studies. It was advocated in many of the discussed studies that integration between various sectors is necessary for more effective air quality management. Therefore, urban vegetation system development should be considered alongside other spatial development issues. In many other planning fields, such as the transportation system and urban mobility management or energy management, urban air pollution mitigation is still insufficiently addressed (XI). It is also crucial that the actions aimed at air quality management are coordinated between various institutions and stakeholder, as, for example, non-governmental organisations as well as academic experts also bring valuable insights to the process of air quality management (XII). Moreover, educating the residents and including them into the process of decision-making may also bring some valuable solutions and joint initiatives (XIII).

An architect emphasised that the inadequate consideration for the urban vegetation system is a result of not integrating its development with the general strategies for the spatial development of the city (XIV).Another deficiency of the current planning system was also mentioned by other local architects: in their opinion, currently only a few new building projects have pro-ecological design solutions, such as green roofs or installation systems, which would allow for considerable energy recovery or enough vegetation to effectively remove pollutants at the local level. This may be related to a lack of appropriate provisions in the existing planning documents, especially the LSDPs, but also in other legal frameworks (XV). A similar conclusion can also be drawn from the analysis of the LSDPs. However, it is important to note that the issue is not that straightforward since in some cases urban planners are not allowed to include more detailed provisions for some legal reasons (XVI). Therefore, this issue requires further analyses. Finally, improper management of the existing greenery was also emphasised (XVII). Such suggestions can also be found in some of the reviewed studies, for example, in the case of near-road vegetation barriers, which require proper maintenance in order to be more efficient in pollution removal or in limiting the exposure of pedestrians to traffic-related emission. The local experts also noticed that a process of changing the biologically vital surfaces to impervious surfaces could be observed in different parts of the city, which may inhibit the growth of tall vegetation (XVII).

5. Discussion and Conclusions

The impact of the urban vegetation system on air quality improvement was reviewed in recent studies. They were divided into three main categories: studies accounting for the deposition effects, studies accounting for the aerodynamic effects, and studies in which both effects were considered. Emphasis was placed on delivering a critical evaluation of the applicability of the currently available results and research tools in the local urban planning practice. Based on the conducted review, the following general conclusions can be drawn:

1. The practical design implications of the results are still too limited to provide general guidelines for urban vegetation management. Their relevance is usually restricted to the investigated location because each study provides guidelines and specific design suggestions applicable only in a certain context, i.e., for different climatic, meteorological, or morphological conditions. Therefore, the provided results cannot be easily transferred to other urban regions and separate local studies are recommended. On the other hand, the described methods and research approaches can be used in other contexts.
2. In the case of deposition effects, local studies are needed in order to establish which of the species or which vegetation forms common to a particular geographical location are most effective in air pollution removal. In such studies, a variety of species and design scenarios as well as various pollutants should be included. Moreover, seasonal changes and various meteorological conditions should be considered. The results of the studies with a limited scope should not be treated as conclusive to comprehensively inform long-term policy-making. Finally, air pollution removal by vegetation should be controlled not only locally, but also at the neighbourhood and municipal scale, especially given the fact that the removal capacity of species-specific pollutants may be affected by various external factors, including wind conditions or local air pollution concentration levels.
3. In case of the aerodynamic effects, the majority of the studies were restricted to the local scale and only in some of them was the neighbourhood scale applied. The obtained results strongly depended on the design of the studies and the applied boundary conditions, which indicates that each design case should be considered separately. However, many of the proposed research

approaches are still too computationally expensive or time consuming to be considered as versatile urban planning tools. Therefore, their further development is required. For the time being, they may be used to investigate particular problem areas, such as street canyons or near-road locations.

4. Studies accounting for both deposition and aerodynamic effects can provide the most comprehensive results, but they are also very complex and much less frequently conducted. Similarly to the two previous cases, the current results do not provide generally applicable guidelines and local studies in which the local conditions are considered are needed for particular design scenarios.
5. Implementing the most beneficial scenario in terms of vegetation design is not always possible in practice. Therefore, as well as developing more accurate methods to quantify pollution removal by plants and more efficient modelling tools, which would allow for the inclusion of more complex geometries and larger computational domains, it is also important to provide decision support tools for optimal greenery arrangement. Such tools should account for many practical aspects such as budget limitations.

Further research is needed on the process of vegetation management for air quality improvement. For example, it would be beneficial to further explore how the various parameters of the urban form (e.g., urban morphology or land use) influence vegetation-dependant local air quality. A statistical approach could serve such a purpose, bringing new insights into the coupled effects of the urban structure and urban vegetation on air quality. Moreover, for the purpose of further studies, more accurate information on the characteristics of urban vegetation will be useful. Therefore, developing increasingly effective and rapid methods for vegetation inventories are required, including, for example, the LiDAR technique [73,132], or more accurate indicators to describe the structural parameters of vegetation, allowing one to detect, for example, seasonal structural changes [133,134]. Finally, developing more accurate models of vegetation in air flow studies, including both modelling approaches and wind tunnel experiments, is advocated [91,135].

The issue of practical applications of the results and providing decision-support tools for urban vegetation management should be explored in more detail in future research. Analysis of the local planning systems in the three selected cities showed that in many cases, the current knowledge regarding the impact of urban vegetation on air quality is not considered in the formulation of urban planning provisions. However, this analysis was preliminary in its character and more comprehensive studies of these planning documents are required in the future to propose more specific recommendations. Other prospects for further research include analyses at different planning levels, including the strategic documents for the development of municipal spatial development policy, which are the grounds for more detailed local plans. Moreover, it should be extended to other Polish cities. Finally, comparisons of planning tools between different countries will also bring beneficial effects. Such comparative studies can be very challenging due to methodological difficulties, such as the lack of compatible data or corresponding information [136]. However, they can also provide some valuable insights because the transferability of planning and design solutions for air quality improvement can be examined.

Finally, prospects for further research are also related to the conducted pilot study. At this stage of research, only a limited number of local experts were included. It was due to the fact that it was difficult to find respondents who had sufficient understanding and experience, since the issue of the effects of vegetation on urban air quality is still not present in the planning practice and discussed in public debate to a sufficient degree. The experts' comments were used to indicate some new approaches towards urban air quality mitigation and its integration with urban planning and to explore future directions for research and planning practice. However, it would be beneficial to expand the scope of the social study by including more experts, also from other cities, as well as by incorporating quantitative social techniques. It is our recommendation that further, more detailed studies in this direction are needed.

Novel decision-support tools for urban planners and policy-makers are necessary to increase the efficiency of air quality management in urban areas [137–140]. Moreover, sectoral and disciplinary approaches are no longer sufficient to integrate urban planning and environmental objectives into comprehensive systems [6], so the issue of air quality improvement cannot be separated from other environmental issues. A common platform is needed to integrate solutions for mitigating noise pollution [141] or light pollution [142,143], controlling local climate and improving thermal comfort [144–148], or reducing energy consumption [149]. Finally, adequate consideration of air quality improvement and its inclusion in the process of the development of the built environment is also related to the social approach towards this issue. If the decision makers fail to provide high-quality planning documents, which will restrict chaotic development and impose the implementation of good design and urban planning practice, urban vegetation systems will merely play an aesthetic role.

Author Contributions: Conceptualization, J.B.; writing—original draft preparation, J.B.; visualization, J.B.; writing—review and editing, J.B., M.D., and A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partly founded from statutory funds of Gdańsk University of Technology, Faculty of Architecture.

Acknowledgments: The authors also gratefully acknowledge the support from the local stakeholders for providing the municipal geospatial datasets.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. World Bank Group World Bank Open Data. Available online: https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS (accessed on 15 May 2018).
2. Eurostat. *Urban Europe: Statistics on Cities, Towns and Suburbs*, 2016 ed.; Publications office of the European Union: Luxembourg, 2016.
3. Xu, L.Y.; Xie, X.D.; Li, S. Correlation analysis of the urban heat island effect and the spatial and temporal distribution of atmospheric particulates using TM images in Beijing. *Environ. Pollut.* **2013**, *178*, 102–114. [CrossRef]
4. WHO Ambient (Outdoor) Air Quality and Health. Available online: http://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (accessed on 15 May 2018).
5. Lelieveld, J.; Klingmüller, K.; Pozzer, A.; Pöschl, U.; Fnais, M.; Daiber, A.; Münzel, T. Cardiovascular disease burden from ambient air pollution in Europe reassessed using novel hazard ratio functions. *Eur. Heart J.* **2019**, *40*, 1590–1596. [CrossRef]
6. Brand, P.; Thomas, M.J. *Urban Environmentalism*; Routledge: New York, NY, USA, 2005.
7. Zhang, Y.; Gu, Z. Air quality by urban design. *Nat. Geosci.* **2013**, *6*, 506. [CrossRef]
8. Yuan, C.; Ng, E.; Norford, L.K. Improving air quality in high-density cities by understanding the relationship between air pollutant dispersion and urban morphologies. *Build. Environ.* **2014**, *71*, 245–258. [CrossRef]
9. Santiago, J.-L.; Buccolieri, R.; Rivas, E.; Sanchez, B.; Martilli, A.; Gatto, E.; Martín, F. On the Impact of Trees on Ventilation in a Real Street in Pamplona, Spain. *Atmosphere* **2019**, *10*, 697. [CrossRef]
10. Guidolotti, G.; Salviato, M.; Calfapietra, C. Comparing estimates of EMEP MSC-W and UFORE models in air pollutant reduction by urban trees. *Environ. Sci. Pollut. Res.* **2016**, *23*, 19541–19550. [CrossRef]
11. Kwak, M.J.; Lee, J.; Kim, H.; Park, S.; Lim, Y.; Kim, J.E.; Baek, S.G.; Seo, S.M.; Kim, K.N.; Woo, S.Y. The Removal Efficiencies of Several Temperate Tree Species at Adsorbing Airborne Particulate Matter in Urban Forests and Roadsides. *Forests* **2019**, *10*, 960. [CrossRef]
12. Liu, J.; Cao, Z.; Zou, S.; Liu, H.; Hai, X.; Wang, S.; Duan, J.; Xi, B.; Yan, G.; Zhang, S.; et al. An investigation of the leaf retention capacity, efficiency and mechanism for atmospheric particulate matter of five greening tree species in Beijing, China. *Sci. Total Environ.* **2018**, *616–617*, 417–426. [CrossRef]
13. Chen, L.; Liu, C.; Zhang, L.; Zou, R.; Zhang, Z. Variation in Tree Species Ability to Capture and Retain Airborne Fine Particulate Matter (PM2.5). *Sci. Rep.* **2017**, *7*, 3206. [CrossRef]
14. Abhijith, K.V.; Kumar, P. Field investigations for evaluating green infrastructure effects on air quality in open-road conditions. *Atmos. Environ.* **2019**, 132–147. [CrossRef]

15. Dadvand, P.; Rivas, I.; Basagaña, X.; Alvarez-Pedrerol, M.; Su, J.; De Castro Pascual, M.; Amato, F.; Jerret, M.; Querol, X.; Sunyer, J.; et al. The association between greenness and traffic-related air pollution at schools. *Sci. Total Environ.* **2015**, *523*, 59–63. [CrossRef]
16. Silli, V.; Salvatori, E.; Manes, F. Removal of airborne particulate matter by vegetation in an urban park in the city of Rome (Italy): An ecosystem services perspective. *Ann. di Bot.* **2015**, *5*, 53–62.
17. Tong, Z.; Whitlow, T.H.; Landers, A.; Flanner, B. A case study of air quality above an urban roof top vegetable farm. *Environ. Pollut.* **2016**, *208*, 256–260. [CrossRef] [PubMed]
18. Van Ryswyk, K.; Prince, N.; Ahmed, M.; Brisson, E.; Miller, J.D.; Villeneuve, P.J. Does urban vegetation reduce temperature and air pollution concentrations? Findings from an environmental monitoring study of the Central Experimental Farm in Ottawa, Canada. *Atmos. Environ.* **2019**, *218*, 116886. [CrossRef]
19. Viippola, V.; Whitlow, T.H.; Zhao, W.; Yli-Pelkonen, V.; Mikola, J.; Pouyat, R.; Setälä, H. The effects of trees on air pollutant levels in peri-urban near-road environments. *Urban For. Urban Green.* **2018**, *30*, 62–71. [CrossRef]
20. Yli-Pelkonen, V.; Scott, A.A.; Viippola, V.; Setälä, H. Trees in urban parks and forests reduce O3, but not NO2 concentrations in Baltimore, MD, USA. *Atmos. Environ.* **2017**, *167*, 73–80. [CrossRef]
21. Yli-Pelkonen, V.; Setälä, H.; Viippola, V. Urban forests near roads do not reduce gaseous air pollutant concentrations but have an impact on particles levels. *Landsc. Urban Plan.* **2017**, *158*, 39–47. [CrossRef]
22. Yli-Pelkonen, V.; Viippola, V.; Rantalainen, A.-L.; Zheng, J.; Setälä, H. The impact of urban trees on concentrations of PAHs and other gaseous air pollutants in Yanji, northeast China. *Atmos. Environ.* **2018**, *192*, 151–159. [CrossRef]
23. Fuller, C.; Carter, D.; Hayat, M.; Baldauf, R.; Watts Hull, R. Phenology of a Vegetation Barrier and Resulting Impacts on Near-Highway Particle Number and Black Carbon Concentrations on a School Campus. *Int. J. Environ. Res. Public Health* **2017**, *14*, 160. [CrossRef]
24. Gómez-Moreno, F.J.; Artíñano, B.; Ramiro, E.D.; Barreiro, M.; Núñez, L.; Coz, E.; Dimitroulopoulou, C.; Vardoulakis, S.; Yagüe, C.; Maqueda, G.; et al. Urban vegetation and particle air pollution: Experimental campaigns in a traffic hotspot. *Environ. Pollut.* **2019**, *247*, 195–205. [CrossRef]
25. Irga, P.J.; Burchett, M.D.; Torpy, F.R. Does urban forestry have a quantitative effect on ambient air quality in an urban environment? *Atmos. Environ.* **2015**, *120*, 173–181. [CrossRef]
26. Klingberg, J.; Broberg, M.; Strandberg, B.; Thorsson, P.; Pleijel, H. Influence of urban vegetation on air pollution and noise exposure—A case study in Gothenburg, Sweden. *Sci. Total Environ.* **2017**, *599–600*, 1728–1739. [CrossRef] [PubMed]
27. Lee, E.S.; Ranasinghe, D.R.; Ahangar, F.E.; Amini, S.; Mara, S.; Choi, W.; Paulson, S.; Zhu, Y. Field evaluation of vegetation and noise barriers for mitigation of near-freeway air pollution under variable wind conditions. *Atmos. Environ.* **2018**, *175*, 92–99. [CrossRef]
28. Lin, M.-Y.; Hagler, G.; Baldauf, R.; Isakov, V.; Lin, H.-Y.; Khlystov, A. The effects of vegetation barriers on near-road ultrafine particle number and carbon monoxide concentrations. *Sci. Total Environ.* **2016**, *553*, 372–379. [CrossRef]
29. Luo, H.; Wang, N.; Chen, J.; Ye, X.; Sun, Y.F. Study on the thermal effects and air quality improvement of green roof. *Sustainability* **2015**, *7*, 2804–2817. [CrossRef]
30. Nguyen, T.; Yu, X.; Zhang, Z.; Liu, M.; Liu, X. Relationship between types of urban forest and PM2.5 capture at three growth stages of leaves. *J. Environ. Sci.* **2015**, *27*, 33–41. [CrossRef]
31. Lu, S.; Yang, X.; Li, S.; Chen, B.; Jiang, Y.; Wang, D.; Xu, L. Effects of plant leaf surface and different pollution levels on PM2.5 adsorption capacity. *Urban For. Urban Green.* **2018**, *34*, 64–70. [CrossRef]
32. Mori, J.; Hanslin, H.M.; Burchi, G.; Sæbø, A. Particulate matter and element accumulation on coniferous trees at different distances from a highway. *Urban For. Urban Green.* **2015**, *14*, 170–177. [CrossRef]
33. Mori, J.; Sæbø, A.; Hanslin, H.M.; Teani, A.; Ferrini, F.; Fini, A.; Burchi, G. Deposition of traffic-related air pollutants on leaves of six evergreen shrub species during a Mediterranean summer season. *Urban For. Urban Green.* **2015**, *14*, 264–273. [CrossRef]
34. Ozdemir, H. Mitigation impact of roadside trees on fine particle pollution. *Sci. Total Environ.* **2019**, *659*, 1176–1185. [CrossRef]
35. Viecco, M.; Vera, S.; Jorquera, H.; Bustamante, W.; Gironás, J.; Dobbs, C.; Leiva, E. Potential of particle matter dry deposition on green roofs and living walls vegetation for mitigating urban atmospheric pollution in semiarid climates. *Sustainability* **2018**, *10*, 2431. [CrossRef]

36. He, C.; Qiu, K.; Alahmad, A.; Pott, R. Particulate matter capturing capacity of roadside evergreen vegetation during the winter season. *Urban For. Urban Green.* **2020**, *48*, 126510. [CrossRef]
37. Leonard, R.J.; McArthur, C.; Hochuli, D.F. Particulate matter deposition on roadside plants and the importance of leaf trait combinations. *Urban For. Urban Green.* **2016**, *20*, 249–253. [CrossRef]
38. Liang, D.; Ma, C.; Wang, Y.Q.; Wang, Y.J.; Chen-xi, Z. Quantifying PM2.5 capture capability of greening trees based on leaf factors analyzing. *Environ. Sci. Pollut. Res.* **2016**, *23*, 21176–21186. [CrossRef] [PubMed]
39. Lin, L.; Yan, J.; Ma, K.; Zhou, W.; Chen, G.; Tang, R.; Zhang, Y. Characterization of particulate matter deposited on urban tree foliage: A landscape analysis approach. *Atmos. Environ.* **2017**, *171*, 59–69. [CrossRef]
40. Luo, J.; Niu, Y.; Zhang, Y.; Zhang, M.; Tian, Y.; Zhou, X. Dynamic analysis of retention PM 2.5 by plant leaves in rainfall weather conditions of six tree species. *Energy Sources Part A Recover. Util. Environ. Eff.* **2019**, 1–12.
41. Perini, K.; Ottelé, M.; Giulini, S.; Magliocco, A.; Roccotiello, E. Quantification of fine dust deposition on different plant species in a vertical greening system. *Ecol. Eng.* **2017**, *100*, 268–276. [CrossRef]
42. Rindy, J.E.; Ponette-González, A.G.; Barrett, T.E.; Sheesley, R.J.; Weathers, K.C. Urban Trees Are Sinks for Soot: Elemental Carbon Accumulation by Two Widespread Oak Species. *Environ. Sci. Technol.* **2019**, *53*, 10092–10101. [CrossRef]
43. Sgrigna, G.; Sæbø, A.; Gawronski, S.; Popek, R.; Calfapietra, C. Particulate Matter deposition on Quercus ilex leaves in an industrial city of central Italy. *Environ. Pollut.* **2015**, *197*, 187–194. [CrossRef]
44. Vieira, J.; Matos, P.; Mexia, T.; Silva, P.; Lopes, N.; Freitas, C.; Correia, O.; Santos-Reis, M.; Branquinho, C.; Pinho, P. Green spaces are not all the same for the provision of air purification and climate regulation services: The case of urban parks. *Environ. Res.* **2018**, *160*, 306–313. [CrossRef]
45. Wang, H.; Maher, B.A.; Ahmed, I.A.; Davison, B. Efficient Removal of Ultrafine Particles from Diesel Exhaust by Selected Tree Species: Implications for Roadside Planting for Improving the Quality of Urban Air. *Environ. Sci. Technol.* **2019**, *53*, 6906–6916. [CrossRef] [PubMed]
46. Xie, C.; Kan, L.; Guo, J.; Jin, S.; Li, Z.; Chen, D.; Li, X.; Che, S. A dynamic processes study of PM retention by trees under different wind conditions. *Environ. Pollut.* **2018**, *233*, 315–322. [CrossRef] [PubMed]
47. Xu, Y.; Shang, B.; Yuan, X.; Feng, Z.; Calatayud, V. Relationships of CO2 assimilation rates with exposure- and flux-based O3 metrics in three urban tree species. *Sci. Total Environ.* **2018**, *613–614*, 233–239. [CrossRef] [PubMed]
48. Xu, Y.; Xu, W.; Mo, L.; Heal, M.R.; Xu, X.; Yu, X. Quantifying particulate matter accumulated on leaves by 17 species of urban trees in Beijing, China. *Environ. Sci. Pollut. Res.* **2018**, *25*, 12545–12556. [CrossRef] [PubMed]
49. Xu, H.; Wang, W.; Wang, H.; Sun, Y.; Zhong, Z.; Wang, S. Differences in quantity and composition of leaf particulate matter and morphological structures in three evergreen trees and their association in Harbin, China. *Environ. Pollut.* **2019**, *252*, 1772–1790. [CrossRef] [PubMed]
50. Zhang, W.; Wang, B.; Niu, X. Relationship between Leaf Surface Characteristics and Particle Capturing Capacities of Different Tree Species in Beijing. *Forests* **2017**, *8*, 92. [CrossRef]
51. Zhang, W.; Zhang, Z.; Meng, H.; Zhang, T. How Does Leaf Surface Micromorphology of Different Trees Impact Their Ability to Capture Particulate Matter? *Forests* **2018**, *9*, 681. [CrossRef]
52. Zhao, X.; Yan, H.; Liu, M.; Kang, L.; Yu, J.; Yang, R. Relationship between PM 2.5 adsorption and leaf surface morphology in ten urban tree species in Shenyang, China. *Energy Sources Part A Recover. Util. Environ. Eff.* **2019**, *41*, 1029–1039. [CrossRef]
53. Alahabadi, A.; Ehrampoush, M.H.; Miri, M.; Ebrahimi Aval, H.; Yousefzadeh, S.; Ghaffari, H.R.; Ahmadi, E.; Talebi, P.; Abaszadeh Fathabadi, Z.; Babai, F.; et al. A comparative study on capability of different tree species in accumulating heavy metals from soil and ambient air. *Chemosphere* **2017**, *172*, 459–467. [CrossRef]
54. Baraldi, R.; Neri, L.; Costa, F.; Facini, O.; Rapparini, F.; Carriero, G. Ecophysiological and micromorphological characterization of green roof vegetation for urban mitigation. *Urban For. Urban Green.* **2019**, *37*, 24–32. [CrossRef]
55. Blanusa, T.; Fantozzi, F.; Monaci, F.; Bargagli, R. Leaf trapping and retention of particles by holm oak and other common tree species in Mediterranean urban environments. *Urban For. Urban Green.* **2015**, *14*, 1095–1101. [CrossRef]
56. Chaudhary, I.J.; Rathore, D. Suspended particulate matter deposition and its impact on urban trees. *Atmos. Pollut. Res.* **2018**, *9*, 1072–1082. [CrossRef]
57. Chaudhary, I.J.; Rathore, D. Dust pollution: Its removal and effect on foliage physiology of urban trees. *Sustain. Cities Soc.* **2019**, *51*, 101696. [CrossRef]

58. Chen, B.; Lu, S.; Zhao, Y.; Li, S.; Yang, X.; Wang, B.; Zhang, H. Pollution Remediation by Urban Forests: PM2.5 Reduction in Beijing, China. *Polish J. Environ. Stud.* **2016**, *25*, 1873–1881. [CrossRef]
59. Greksa, A.; Ljevnaić-Mašić, B.; Grabić, J.; Benka, P.; Radonić, V.; Blagojević, B.; Sekulić, M. Potential of urban trees for mitigating heavy metal pollution in the city of Novi Sad, Serbia. *Environ. Monit. Assess.* **2019**, *191*, 636. [CrossRef] [PubMed]
60. Bottalico, F.; Travaglini, D.; Chirici, G.; Garfì, V.; Giannetti, F.; De Marco, A.; Fares, S.; Marchetti, M.; Nocentini, S.; Paoletti, E.; et al. A spatially-explicit method to assess the dry deposition of air pollution by urban forests in the city of Florence, Italy. *Urban For. Urban Green.* **2017**, *27*, 221–234. [CrossRef]
61. Douglas, A.N.J.; Irga, P.J.; Torpy, F.R. Determining broad scale associations between air pollutants and urban forestry: A novel multifaceted methodological approach. *Environ. Pollut.* **2019**, *247*, 474–481. [CrossRef]
62. Marando, F.; Salvatori, E.; Fusaro, L.; Manes, F. Removal of PM10 by forests as a nature-based solution for air quality improvement in the Metropolitan city of Rome. *Forests* **2016**, *7*, 150. [CrossRef]
63. Matos, P.; Vieira, J.; Rocha, B.; Branquinho, C.; Pinho, P. Modeling the provision of air-quality regulation ecosystem service provided by urban green spaces using lichens as ecological indicators. *Sci. Total Environ.* **2019**, *665*, 521–530. [CrossRef]
64. Velasco, E.; Roth, M.; Norford, L.; Molina, L.T. Does urban vegetation enhance carbon sequestration? *Landsc. Urban Plan.* **2016**, *148*, 99–107. [CrossRef]
65. Yang, J.; Chang, Y.; Yan, P. Ranking the suitability of common urban tree species for controlling PM 2.5 pollution. *Atmos. Pollut. Res.* **2015**, *6*, 267–277. [CrossRef]
66. Zhao, S.; Tang, Y.; Chen, A. Carbon Storage and Sequestration of Urban Street Trees in Beijing, China. *Front. Ecol. Evol.* **2016**, *4*. [CrossRef]
67. Bodnaruk, E.W.; Kroll, C.N.; Yang, Y.; Hirabayashi, S.; Nowak, D.J.; Endreny, T.A. Where to plant urban trees? A spatially explicit methodology to explore ecosystem service tradeoffs. *Landsc. Urban Plan.* **2017**, *157*, 457–467. [CrossRef]
68. Jayasooriya, V.M.; Ng, A.W.M.; Muthukumaran, S.; Perera, B.J.C. Green infrastructure practices for improvement of urban air quality. *Urban For. Urban Green.* **2017**, *21*, 34–47. [CrossRef]
69. Kiss, M.; Takács, Á.; Pogácsás, R.; Gulyás, Á. The role of ecosystem services in climate and air quality in urban areas: Evaluating carbon sequestration and air pollution removal by street and park trees in Szeged (Hungary). *Morav. Geogr. Rep.* **2015**, *23*, 36–46. [CrossRef]
70. Ning, Z.; Chambers, R.; Abdollahi, K. Modeling air pollutant removal, carbon storage, and CO2 sequestration potential of urban forests in Scotlandville, Louisiana, USA. *iForest Biogeosciences For.* **2016**, *9*, 860–867. [CrossRef]
71. Selmi, W.; Weber, C.; Rivière, E.; Blond, N.; Mehdi, L.; Nowak, D. Air pollution removal by trees in public green spaces in Strasbourg city, France. *Urban For. Urban Green.* **2016**, *17*, 192–201. [CrossRef]
72. Wu, J.; Wang, Y.; Qiu, S.; Peng, J. Using the modified i-Tree Eco model to quantify air pollution removal by urban vegetation. *Sci. Total Environ.* **2019**, *688*, 673–683. [CrossRef]
73. Zhao, Y.; Hu, Q.; Li, H.; Wang, S.; Ai, M. Evaluating carbon sequestration and PM2.5 removal of urban street trees using mobile laser scanning data. *Remote Sens.* **2018**, *10*, 1759. [CrossRef]
74. Yang, J.; Liu, H.; Sun, J. Evaluation and Application of an Online Coupled Modeling System to Assess the Interaction between Urban Vegetation and Air Quality. *Aerosol Air Qual. Res.* **2018**, *18*, 693–710. [CrossRef]
75. Hofman, J.; Bartholomeus, H.; Janssen, S.; Calders, K.; Wuyts, K.; Van Wittenberghe, S.; Samson, R. Influence of tree crown characteristics on the local PM 10 distribution inside an urban street canyon in Antwerp (Belgium): A model and experimental approach. *Urban For. Urban Green.* **2016**, *20*, 265–276. [CrossRef]
76. Neft, I.; Scungio, M.; Culver, N.; Singh, S. Simulations of aerosol filtration by vegetation: Validation of existing models with available lab data and application to near-roadway scenario. *Aerosol Sci. Technol.* **2016**, *50*, 937–946. [CrossRef]
77. Giometto, M.G.; Christen, A.; Egli, P.E.; Schmid, M.F.; Tooke, R.T.; Coops, N.C.; Parlange, M.B. Effects of trees on mean wind, turbulence and momentum exchange within and above a real urban environment. *Adv. Water Resour.* **2017**, *106*, 154–168. [CrossRef]
78. Sun, D.; Zhang, Y. Influence of avenue trees on traffic pollutant dispersion in asymmetric street canyons: Numerical modeling with empirical analysis. *Transp. Res. Part D Transp. Environ.* **2018**, *65*, 784–795. [CrossRef]

79. Jeanjean, A.P.R.; Hinchliffe, G.; McMullan, W.A.; Monks, P.S.; Leigh, R.J. A CFD study on the effectiveness of trees to disperse road traffic emissions at a city scale. *Atmos. Environ.* **2015**, *120*, 1–14. [CrossRef]
80. Buccolieri, R.; Jeanjean, A.P.R.; Gatto, E.; Leigh, R.J. The impact of trees on street ventilation, NOx and PM2.5 concentrations across heights in Marylebone Rd street canyon, central London. *Sustain. Cities Soc.* **2018**, *41*, 227–241. [CrossRef]
81. Xing, Y.; Brimblecombe, P. Dispersion of traffic derived air pollutants into urban parks. *Sci. Total Environ.* **2018**, *622–623*, 576–583. [CrossRef]
82. Tong, Z.; Whitlow, T.H.; MacRae, P.F.; Landers, A.J.; Harada, Y. Quantifying the effect of vegetation on near-road air quality using brief campaigns. *Environ. Pollut.* **2015**, *201*, 141–149. [CrossRef]
83. Gromke, C.; Jamarkattel, N.; Ruck, B. Influence of roadside hedgerows on air quality in urban street canyons. *Atmos. Environ.* **2016**, *139*, 75–86. [CrossRef]
84. Yuan, C.; Norford, L.; Ng, E. A semi-empirical model for the effect of trees on the urban wind environment. *Landsc. Urban Plan.* **2017**, *168*, 84–93. [CrossRef]
85. Abhijith, K.V.; Gokhale, S. Passive control potentials of trees and on-street parked cars in reduction of air pollution exposure in urban street canyons. *Environ. Pollut.* **2015**, *204*, 99–108. [CrossRef]
86. Ghasemian, M.; Amini, S.; Princevac, M. The influence of roadside solid and vegetation barriers on near-road air quality. *Atmos. Environ.* **2017**, *170*, 108–117. [CrossRef]
87. Gromke, C.; Blocken, B. Influence of avenue-trees on air quality at the urban neighborhood scale. Part I: Quality assurance studies and turbulent Schmidt number analysis for RANS CFD simulations. *Environ. Pollut.* **2015**, *196*, 214–223. [CrossRef]
88. Gromke, C.; Blocken, B. Influence of avenue-trees on air quality at the urban neighborhood scale. Part II: Traffic pollutant concentrations at pedestrian level. *Environ. Pollut.* **2015**, *196*, 176–184. [CrossRef]
89. Huang, Y.; Li, M.; Ren, S.; Wang, M.; Cui, P. Impacts of tree-planting pattern and trunk height on the airflow and pollutant dispersion inside a street canyon. *Build. Environ.* **2019**, *165*, 106385. [CrossRef]
90. Merlier, L.; Jacob, J.; Sagaut, P. Lattice-Boltzmann Large-Eddy Simulation of pollutant dispersion in street canyons including tree planting effects. *Atmos. Environ.* **2018**, *195*, 89–103. [CrossRef]
91. Su, J.; Wang, L.; Gu, Z.; Song, M.; Cao, Z. Effects of real trees and their structure on pollutant dispersion and flow field in an idealized street canyon. *Atmos. Pollut. Res.* **2019**, *10*, 1699–1710. [CrossRef]
92. Li, X.-B.B.; Lu, Q.-C.C.; Lu, S.-J.J.; He, H.-D.D.; Peng, Z.-R.R.; Gao, Y.; Wang, Z.-Y.Y. The impacts of roadside vegetation barriers on the dispersion of gaseous traffic pollution in urban street canyons. *Urban For. Urban Green.* **2016**, *17*, 80–91. [CrossRef]
93. Di Sabatino, S.; Buccolieri, R.; Pappaccogli, G.; Leo, L.S. The effects of trees on micrometeorology in a real street canyon: Consequences for local air quality. *Int. J. Environ. Pollut.* **2015**, *58*, 100. [CrossRef]
94. Moradpour, M.; Afshin, H.; Farhanieh, B. A numerical investigation of reactive air pollutant dispersion in urban street canyons with tree planting. *Atmos. Pollut. Res.* **2017**, *8*, 253–266. [CrossRef]
95. Wang, C.; Li, Q.; Wang, Z.-H. Quantifying the impact of urban trees on passive pollutant dispersion using a coupled large-eddy simulation–Lagrangian stochastic model. *Build. Environ.* **2018**, *145*, 33–49. [CrossRef]
96. Kurppa, M.; Hellsten, A.; Auvinen, M.; Raasch, S.; Vesala, T.; Järvi, L. Ventilation and air quality in city blocks using large-eddy simulation-urban planning perspective. *Atmosphere* **2018**, *9*, 65. [CrossRef]
97. Jeanjean, A.P.R.; Buccolieri, R.; Eddy, J.; Monks, P.S.; Leigh, R.J. Air quality affected by trees in real street canyons: The case of Marylebone neighbourhood in central London. *Urban For. Urban Green.* **2017**, *22*, 41–53. [CrossRef]
98. Santiago, J.-L.; Martilli, A.; Martin, F. On Dry Deposition Modelling of Atmospheric Pollutants on Vegetation at the Microscale: Application to the Impact of Street Vegetation on Air Quality. *Bound. Layer Meteorol.* **2017**, *162*, 451–474. [CrossRef]
99. Akopov, A.S.; Beklaryan, L.A.; Saghatelyan, A.K. Agent-based modelling of interactions between air pollutants and greenery using a case study of Yerevan, Armenia. *Environ. Model. Softw.* **2019**, *116*, 7–25. [CrossRef]
100. Chen, L.; Liu, C.; Zou, R.; Yang, M.; Zhang, Z. Experimental examination of effectiveness of vegetation as bio-filter of particulate matters in the urban environment. *Environ. Pollut.* **2016**, *208*, 198–208. [CrossRef]
101. Xue, F.; Li, X. The impact of roadside trees on traffic released PM10 in urban street canyon: Aerodynamic and deposition effects. *Sustain. Cities Soc.* **2017**, *30*, 195–204. [CrossRef]

102. Zhang, M.; Deshmukh, P.; Baldauf, R.; Venkatram, A.; Isakov, V. Evaluation and development of tools to quantify the impacts of roadside vegetation barriers on near-road air quality. *Int. J. Environ. Pollut.* **2017**, *62*, 127. [CrossRef]
103. Jeanjean, A.P.R.; Monks, P.S.; Leigh, R.J. Modelling the effectiveness of urban trees and grass on PM2.5reduction via dispersion and deposition at a city scale. *Atmos. Environ.* **2016**, *147*, 1–10. [CrossRef]
104. Jeanjean, A.P.R.; Gallagher, J.; Monks, P.S.; Leigh, R.J. Ranking current and prospective NO 2 pollution mitigation strategies: An environmental and economic modelling investigation in Oxford Street, London. *Environ. Pollut.* **2017**, *225*, 587–597. [CrossRef]
105. Morakinyo, T.E.; Lam, Y.F. Study of traffic-related pollutant removal from street canyon with trees: Dispersion and deposition perspective. *Environ. Sci. Pollut. Res.* **2016**, *23*, 21652–21668. [CrossRef] [PubMed]
106. Rui, L.; Buccolieri, R.; Gao, Z.; Ding, W.; Shen, J. The impact of green space layouts on microclimate and air quality in residential districts of Nanjing, China. *Forests* **2018**, *9*, 224. [CrossRef]
107. Santiago, J.-L.; Rivas, E.; Sanchez, B.; Buccolieri, R.; Martin, F. The Impact of Planting Trees on NOx Concentrations: The Case of the Plaza de la Cruz Neighborhood in Pamplona (Spain). *Atmosphere* **2017**, *8*, 131. [CrossRef]
108. Tong, Z.; Baldauf, R.W.; Isakov, V.; Deshmukh, P.; Max Zhang, K. Roadside vegetation barrier designs to mitigate near-road air pollution impacts. *Sci. Total Environ.* **2016**, *541*, 920–927. [CrossRef] [PubMed]
109. Vranckx, S.; Vos, P.; Maiheu, B.; Janssen, S. Impact of trees on pollutant dispersion in street canyons: A numerical study of the annual average effects in Antwerp, Belgium. *Sci. Total Environ.* **2015**, *532*, 474–483. [CrossRef]
110. Deng, S.; Ma, J.; Zhang, L.; Jia, Z.; Ma, L. Microclimate simulation and model optimization of the effect of roadway green space on atmospheric particulate matter. *Environ. Pollut.* **2019**, *246*, 932–944. [CrossRef]
111. Santiago, J.-L.; Buccolieri, R.; Rivas, E.; Calvete-Sogo, H.; Sanchez, B.; Martilli, A.; Alonso, R.; Elustondo, D.; Santamaría, J.M.; Martin, F. CFD modelling of vegetation barrier effects on the reduction of traffic-related pollutant concentration in an avenue of Pamplona, Spain. *Sustain. Cities Soc.* **2019**, *48*, 101559. [CrossRef]
112. Xing, Y.; Brimblecombe, P. Role of vegetation in deposition and dispersion of air pollution in urban parks. *Atmos. Environ.* **2019**, *201*, 73–83. [CrossRef]
113. Jin, X.; Yang, L.; Du, X.; Yang, Y. Transport characteristics of PM2.5 inside urban street canyons: The effects of trees and vehicles. *Build. Simul.* **2017**, *10*, 337–350. [CrossRef]
114. Hong, B.; Lin, B.; Qin, H. Numerical Investigation on the Effect of Avenue Trees on PM2.5 Dispersion in Urban Street Canyons. *Atmosphere* **2017**, *8*, 129. [CrossRef]
115. Qin, H.; Hong, B.; Jiang, R. Are green walls better options than green roofs for mitigating PM10 pollution? CFD simulations in urban street canyons. *Sustainability* **2018**, *10*, 2833. [CrossRef]
116. Rafael, S.; Vicente, B.; Rodrigues, V.; Miranda, A.I.; Borrego, C.; Lopes, M. Impacts of green infrastructures on aerodynamic flow and air quality in Porto's urban area. *Atmos. Environ.* **2018**, *190*, 317–330. [CrossRef]
117. Fallmann, J.; Forkel, R.; Emeis, S. Secondary effects of urban heat island mitigation measures on air quality. *Atmos. Environ.* **2016**, *125*, 199–211. [CrossRef]
118. Weber, M.; Driessen, P.P.J. Environmental Policy Integration: The Role of Policy Windows in the Integration of Noise and Spatial Planning. *Environ. Plan. C Gov. Policy* **2010**, *28*, 1120–1134. [CrossRef]
119. Ren, C.; Yang, R.; Cheng, C.; Xing, P.; Fang, X.; Zhang, S.; Wang, H.; Shi, Y.; Zhang, X.; Kwok, Y.T.; et al. Creating breathing cities by adopting urban ventilation assessment and wind corridor plan – The implementation in Chinese cities. *J. Wind Eng. Ind. Aerodyn.* **2018**, *182*, 170–188. [CrossRef]
120. *The Study on Conditions and Spatial Development Directions for Gdańsk*; Gdańsk Development Office: Gdańsk, Poland, 2018. (In Polish)
121. Osińska-Skotak, K.; Zawalich, J. Analysis of land use changes of urban ventilation corridors in Warsaw in 1992–2015. *Geogr. Pol.* **2016**, *89*, 345–358. [CrossRef]
122. *The Study on Conditions and Spatial Development Directions for Warsaw*; Architecture and Spatial Planning Office of the Capital City of Warsaw: Warsaw, Poland, 2004. (In Polish)
123. *The Study on Conditions and Spatial Development Directions for Poznań*; Poznań Municipal Urban Planning Office: Poznań, Poland, 2018. (In Polish)
124. Badach, J.; Raszeja, E. Developing a framework for the implementation of landscape and greenspace indicators in sustainable urban planning. Waterfront landscape management: Case studies in Gdańsk, Poznań and Bristol. *Sustainability* **2019**, *11*, 2291. [CrossRef]

125. Kotus, J. Changes in the spatial structure of a large Polish city—The case of Poznań. *Cities* **2006**, *23*, 364–381. [CrossRef]
126. Łowicki, D. Land use changes in Poland during transformation. Case study of Wielkopolska region. *Landsc. Urban Plan.* **2008**, *87*, 279–288. [CrossRef]
127. Gdańsk Municipal Office Gdańsk Public Information Bulletin [In Polish]. Available online: https://bip.gdansk.pl/ (accessed on 4 November 2018).
128. Warsaw Architecture and Spatial Planning Office. The Capital City of Warsaw Public Information Bulletin [in Polish]. Available online: https://bip.warszawa.pl (accessed on 1 April 2019).
129. Poznań Municipal Urban Planning Office. Poznań Public Information Bulletin [in Polish]. Available online: http://bip.poznan.pl/ (accessed on 4 November 2018).
130. Szulczewska, B.; Giedych, R.; Borowski, J.; Kuchcik, M.; Sikorski, P.; Mazurkiewicz, A.; Stańczyk, T. How much green is needed for a vital neighbourhood? In search for empirical evidence. *Land Use Policy* **2014**, *38*, 330–345. [CrossRef]
131. Ng, E. Policies and technical guidelines for urban planning of high-density cities - air ventilation assessment (AVA) of Hong Kong. *Build. Environ.* **2009**, *44*, 1478–1488. [CrossRef]
132. Huang, Y.; Yu, B.; Zhou, J.; Hu, C.; Tan, W.; Hu, Z.; Wu, J. Toward automatic estimation of urban green volume using airborne LiDAR data and high resolution Remote Sensing images. *Front. Earth Sci.* **2013**, *7*, 43–54. [CrossRef]
133. Wei, S.; Fang, H.; Schaaf, C.B.; He, L.; Chen, J.M. Global 500 m clumping index product derived from MODIS BRDF data (2001–2017). *Remote Sens. Environ.* **2019**, *232*, 111296. [CrossRef]
134. Wei, S.; Fang, H. Estimation of canopy clumping index from MISR and MODIS sensors using the normalized difference hotspot and darkspot (NDHD) method: The influence of BRDF models and solar zenith angle. *Remote Sens. Environ.* **2016**, *187*, 476–491. [CrossRef]
135. Gromke, C. A vegetation modeling concept for building and environmental aerodynamics wind tunnel tests and its application in pollutant dispersion studies. *Environ. Pollut.* **2011**, *159*, 2094–2099. [CrossRef]
136. Runhaar, H.; Driessen, P.P.J.; Soer, L. Sustainable urban development and the challenge of policy integration: An assessment of planning tools for integrating spatial and environmental planning in the Netherlands. *Environ. Plan. B Plan. Des.* **2009**, *36*, 417–431. [CrossRef]
137. Jensen, S.S.; Berkowicz, R.; Sten Hansen, H.; Hertel, O. A Danish decision-support GIS tool for management of urban air quality and human exposures. *Transp. Res. Part D Transp. Environ.* **2001**, *6*, 229–241. [CrossRef]
138. Lim, L.L.; Hughes, S.J.; Hellawell, E.E. Integrated decision support system for urban air quality assessment. *Environ. Model. Softw.* **2005**, *20*, 947–954. [CrossRef]
139. Guariso, G.; Maione, M.; Volta, M. A decision framework for Integrated Assessment Modelling of air quality at regional and local scale. *Environ. Sci. Policy* **2016**, *65*, 3–12. [CrossRef]
140. Carnevale, C.; Douros, J.; Finzi, G.; Graff, A.; Guariso, G.; Nahorski, Z.; Pisoni, E.; Ponche, J.L.; Real, E.; Turrini, E.; et al. Uncertainty evaluation in air quality planning decisions: A case study for Northern Italy. *Environ. Sci. Policy* **2016**, *65*, 39–47. [CrossRef]
141. Ariza-Villaverde, A.B.; Jiménez-Hornero, F.J.; Gutiérrez De Ravé, E. Influence of urban morphology on total noise pollution: Multifractal description. *Sci. Total Environ.* **2014**, *472*, 1–8. [CrossRef] [PubMed]
142. Zielinska-Dabkowska, K.M.; Xavia, K. Global Approaches to Reduce Light Pollution from Media Architecture and Non-Static, Self-Luminous LED Displays for Mixed-Use Urban Developments. *Sustainability* **2019**, *11*, 3446. [CrossRef]
143. Zielinska-Dabkowska, K.M. Make lighting healthier. *Nature* **2018**, *553*, 274–276. [CrossRef] [PubMed]
144. Stone, B.; Hess, J.J.; Frumkin, H. Urban Form and Extreme Heat Events: Are Sprawling Cities More Vulnerable to Climate Change Than Compact Cities? *Environ. Health Perspect.* **2010**, *118*, 1425–1428. [CrossRef] [PubMed]
145. Krüger, E.L.; Minella, F.O.; Rasia, F. Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil. *Build. Environ.* **2011**, *46*, 621–634. [CrossRef]
146. Stead, D. Urban planning, water management and climate change strategies: Adaptation, mitigation and resilience narratives in the Netherlands. *Int. J. Sustain. Dev. World Ecol.* **2014**, *21*, 15–27. [CrossRef]
147. Ward, K.; Lauf, S.; Kleinschmit, B.; Endlicher, W. Heat waves and urban heat islands in Europe: A review of relevant drivers. *Sci. Total Environ.* **2016**, *569–570*, 527–539. [CrossRef]

148. Xu, M.; Hong, B.; Jiang, R.; An, L.; Zhang, T. Outdoor thermal comfort of shaded spaces in an urban park in the cold region of China. *Build. Environ.* **2019**, *155*, 408–420. [CrossRef]
149. Chen, Y.; Li, X.; Zheng, Y.; Guan, Y.; Liu, X. Estimating the relationship between urban forms and energy consumption: A case study in the Pearl River Delta, 2005–2008. *Landsc. Urban Plan.* **2011**, *102*, 33–42. [CrossRef]