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Characterization of Urban Greening in a District of Lecce (Southern Italy) for the Analysis of CO_2 Storage and Air Pollutant Dispersion

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Abstract: This paper is devoted to the assessment of urban greening effects on two important ecosystem services, i.e., air quality and CO_2 storage, including the corresponding economic impacts in a real urban area, i.e., a district located in the Mediterranean city of Lecce (southern Italy). Two tools were employed, i-Tree Canopy and the computational fluid dynamics (CFD) microclimate model ENVI-met. i-Tree Canopy allowed fully determining the land-cover percentage on the basis of different ground cover classes and obtaining an estimate of annual values of CO_2 storage, air pollutant removal, and economic benefits in the presence of urban greening. The estimate in i-Tree Canopy considered only the amount of greening; therefore, air pollutant removal estimates were only potential. As the vegetation was located in street canyons, its interaction with local meteorology and urban geometry strictly affected the dispersion of nitrogen oxides (NOx) (taken here as an example) as obtained from ENVI-met simulations. In ENVI-met, both deposition/absorption and aerodynamic effects were considered, and local increases in concentration were found in the district. The analysis of results obtained from different tools (one complex (CFD model) and the other simple (i-Tree model)) showed the error associated with the simple model in the computation of impacts if the interaction among the vegetation characteristics, the meteorological conditions, and the urban geometry was neglected; however, it also uncovers a novel approach for comprehensively characterizing a given area in terms of its vegetation cover, CO_2 storage, and economic benefits, as well as local effects on air quality. This study is set in a broader context aimed at assessing the air quality in urban canopies of Mediterranean areas characterized by the presence of narrow street canyons where pollutants can accumulate due to ineffective air exchange with the above atmosphere.

Keywords: air pollutant dispersion; CO_2 storage; economic benefits; urban vegetation; i-Tree Canopy; ENVI-met; Mediterranean city

1. Introduction

Air quality is a major concern for people living in cities, where traffic-related emissions are one of the major contributors to urban air pollution [1]. Urban greening (hedges, trees and parks, green roofs, and large natural spaces) has the ability to reduce air pollution locally and to provide significant health, environmental, social, and cultural benefits [1–6]. Its role is related to several environmental improvements such as decreasing air and surface temperatures via shading and evapotranspiration, removing air pollutants via dry deposition or uptake through leaf stomata (absorption), reducing traffic noise, and storing carbon dioxide (CO_2) [2–4,7]. In this regard, economic studies treat urban trees as if they produce economically valued goods, such as CO_2 sequestration and air pollution reduction; then, they estimate prices for these "goods", and add these prices together to provide the total economic benefit provided by trees, before subtracting the costs of producing and maintaining the urban treescape [3]. Unfortunately, the green infrastructure is not paid enough attention to, especially in growing cities. Green areas do not have the same monetary value as building sites and building volumes in a city. There were attempts to develop toolkits to show the monetary value of urban green infrastructure [8], but they are still under development.

Among the ecosystem services, the impact on urban air quality was documented in several studies, but it is not yet completely established. Recent reviews [3,5,9–12] showed the potential of vegetation, especially trees, in mitigating air pollution, while leaving open questions regarding the impact that trees have on air quality in urban areas, since they may lead to increased or decreased concentrations. In general, air pollutant concentration is affected by vegetation due to two effects: (1) aerodynamic effects (or blocking effects) and (2) removal of air pollutants by deposition/absorption.

As summarized by Grote et al. [10], positive impacts of trees on air quality occur due to the deposition of pollutants on plant surfaces and stomatal uptake (absorption). Deposition rates depend on pollutant concentrations, meteorological conditions, air movement through the crown, transfer through the boundary layer adjacent to surfaces, and absorption capacity of surfaces, which also depend on stomatal conductance. In turn, these depend on species, arrangement, crown, and foliage characteristics. Pollutant removal from the atmosphere also occurs through the influence on microclimate; temperature reduction via shading and evapotranspiration may change the rate of chemical reactions, leading to reduced ozone (O_3) concentrations.

On the other hand, negative impacts of trees on air quality are due to the release of allergenic particulates and harmful biogenic volatile organic compounds (BVOCs) that can act as precursors to smog or ozone formation, especially when nitrogen dioxides (NOx) are present. Furthermore, many studies found that the aerodynamic effects (blocking effects) of trees are more significant than deposition/absorption. In fact, vegetation, particularly trees, by modifying the wind flow around other trees, may obstruct the air exchange and dispersion of traffic-related pollutants, thereby increasing concentrations below the crowns of trees, especially when they are characterized by high leaf area density (LAD). The changes of wind flow within street canyons due to vegetation depends on the vegetation characteristics (location, size, shape of crown, or LAD), local meteorology, and urban geometry. Thus, it is noteworthy that, although vegetation removes air pollutants via deposition/absorption, the pollutant concentration at pedestrian height in a street canyon can decrease or increase depending on the aerodynamic effects of vegetation [5,13–21].

In this context, even though challenges and strategies for green space planning were proposed [22], comprehensive strategies on the use of urban vegetation for air quality purposes are still missing since the effects of urban vegetation are local depending on its interaction with urban morphology and meteorological conditions [23,24]. A careful planning of green spaces is, thus, necessary, and the use of numerical modeling, allowing the investigation of different scenarios, can help in planning and managing urban greening so as to enhance its positive effects.

Within this perspective, the aim of this paper is an assessment of the urban greening effects on two important ecosystem services, i.e., air quality and CO_2 storage, including the corresponding economic impacts in a real urban area, i.e., a district located in the city of Lecce (southern Italy), for which a detailed reconstruction of the morphological and vegetational characteristics is also performed. Two modeling tools are used, the software i-Tree Canopy and the computational fluid dynamics (CFD)-based microclimate model ENVI-met. i-Tree Canopy was recently applied in the scientific literature to quantify green cover and its economic benefits [25–33], while there are no studies applying such a tool in Lecce. ENVI-met was successfully employed in studies analyzing the effects of vegetation on microclimate and thermal comfort in the urban environment, where it was thoroughly described [34–40]; it was also employed for an investigation of air quality, focusing on air pollutant deposition and dispersion in several studies [41–49], which mostly found a satisfactory agreement with observations and concluded that, although it is not a very sophisticated model, it provides sufficient functions for establishing small-scale pollutant distribution for studies of urban greening in near-road environments. Specifically, the model was only applied to evaluate the microclimate in some districts of Lecce [50–52], while, to our knowledge, there are no papers applying the model to evaluate the impact of urban greening on the dispersion of air pollutants in the city of Lecce.

Here, i-Tree Canopy was employed at the district level to obtain an estimate of CO_2 storage, potential air pollutant removal, and economic benefits in the presence of vegetation. On the other hand, ENVI-met was employed at the street level to obtain the impact of vegetation on air pollutant concentration (with nitrogen oxides (NOx) taken as an example) within the streets with high resolution. This model reproduces and simulates the dispersion of air pollutants considering the complex interaction among local meteorology, urban geometry, and vegetation.

The paper is structured as follows: Section 2 presents a brief summary of recent literature studies analyzing air quality and microclimate in the city of Lecce. Section 3 presents the study area (district in Lecce), the tools employed, i.e., i-Tree Canopy and ENVI-met, and their set-up. The vegetational and morphological characterizations of the district, as well as results obtained from the tools, are presented in Section 4. The discussion and conclusions are given in Section 5.

To the best of our knowledge, this paper is the first study, albeit preliminary, to employ two different tools (i-Tree Canopy and ENVI-met) in a district of the city of Lecce to comprehensively characterize the vegetation cover, estimate its economic benefits and CO_2 storage, and evaluate in detail the dispersion of air pollutants due to the interaction among meteorology, urban geometry, and vegetation. This study is a step toward a comprehensive characterization of vegetational characteristics and a better understanding of the impact of vegetation on air quality in a Mediterranean city, which can be extended to other Mediterranean cities. This is in line with the need to develop effective policies of environmental sustainability with respect to air quality in urban canopies of Mediterranean areas characterized by the presence of narrow street canyons where pollutants can accumulate due to a reduced air exchange with the above atmosphere [53].

2. A Brief Overview of Recent Microclimate and Air Quality Studies in Lecce

The city of Lecce (UTM coordinates: 40°21′7.24″ north (N), 18°10′8.9″ east (E)), a medium-sized city representative of Mediterranean cities in terms of architectural design and climate, is located in southern Italy (Figure 1, top). With 96,534 inhabitants [54], it is built on flat land, approximately 40–50 m above sea level (a.s.l.). In the Köppen–Geiger classification, Lecce belongs to the Warm Mediterranean Climate Csa class, with dry and hot summers, due to the domination of subtropical high-pressure systems, and mild and wet winters with moderate and changeable temperatures. The Mediterranean region is potentially vulnerable to climatic changes because it is affected by interactions between mid-latitude and tropical processes, being in a transition zone between the arid climate of North Africa and the temperate and rainy climate of central Europe [55]. The urban morphology is characterized by two- to three-story buildings and narrow street canyons [56]. The city has been the object of studies (some of them considering the effects of vegetation) analyzing microclimate and air quality using both experimental and modeling approaches. Some of the most recent papers are reported here.

As for microclimate, only few studies, both experimental and modeling, were performed. Maggiotto et al. [50,51] discussed the performance of the temperature perturbation-type Atmospheric Dispersion Modelling System (ADMS)—Temperature and Humidity Model (ADMS-TH) and ENVI-met for the prediction of urban air temperature using field measurements they collected in the summer of 2012. Direct comparisons with measured data and statistical indices showed that modeled results were within the range of acceptance. Daily trends were well captured, although an underestimation of maximum temperatures was observed. Overall, ADMS-TH did predict the temperature cycle with higher accuracy than ENVI-met, and its performance was particularly good during the night.

ENVI-met required an ad hoc tuning of surface boundary conditions to satisfactorily predict nocturnal cooling. Gatto et al. [52] applied and validated ENVI-met for the evaluation of thermal comfort in neighborhoods located in two cities characterized by a different climate, i.e., Lecce (taken as a Mediterranean city) and a northern European city in southern Finland (Lahti). Results showed that, at pedestrian height, the presence of vegetation led to an improvement of thermal comfort in the summer in both neighborhoods. In winter, thermal discomfort was observed in the presence of vegetation.

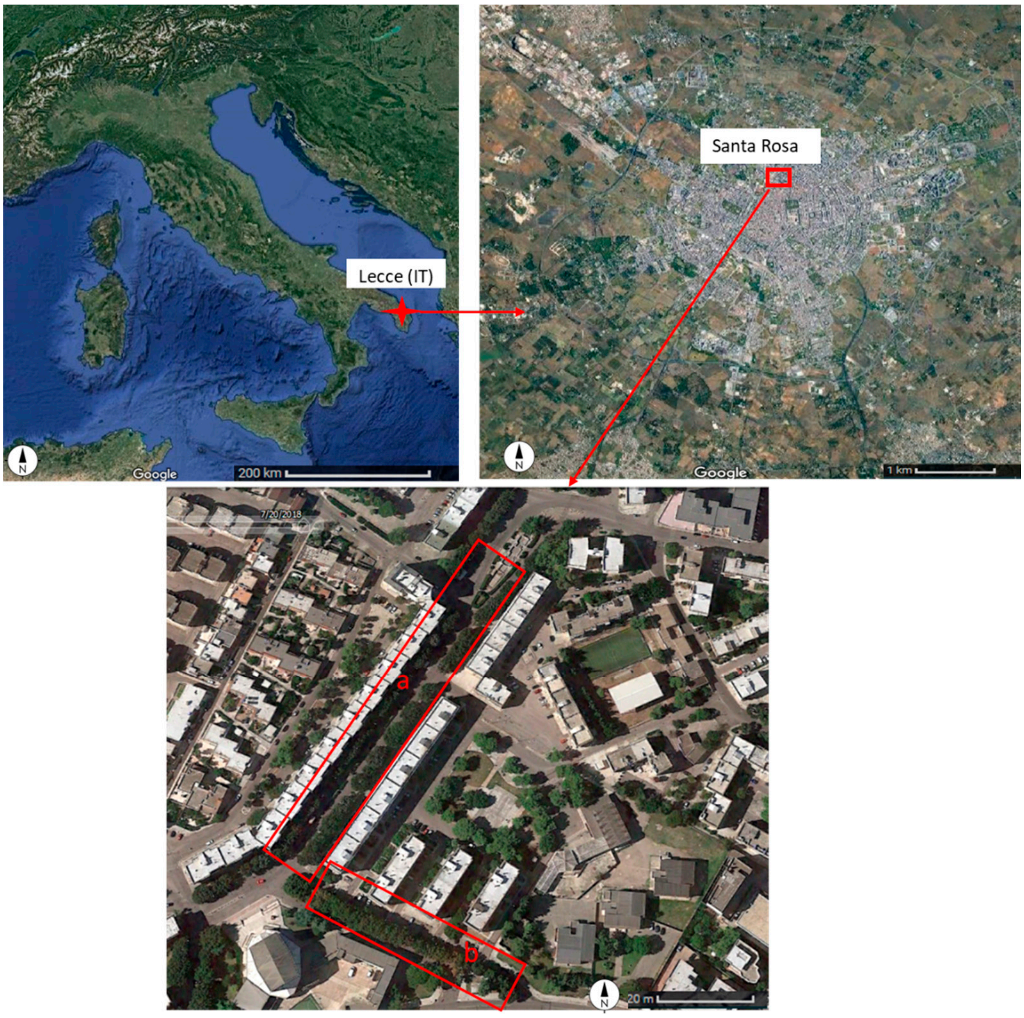

Figure 1. Top: position of the city of Lecce in southern Italy with a focus on the study area (referred to as Santa Rosa hereinafter). Bottom: three-dimensional (3D) view of Santa Rosa with indication of two street canyons ('a" and "b") on which the analysis is focused (modified from Google Earth); see Section 3 for more details.

As for air quality, more studies, both experimental and modeling, were performed in the last five years. Di Sabatino et al. [57] analyzed the effects of trees on local meteorology using field measurements and CFD simulations. Measurements were collected continuously for 51 days in a street canyon with trees to cover different meteorological and foliage conditions. Building façades and ground temperatures were estimated from infrared images, while flow and turbulence were measured by ultrasonic anemometers. It was shown that, in the case of a wind approaching parallel to the street axis, trees induced large wind direction fluctuations below tree crowns and low velocities up to about 80% lower than those recorded at the roof top. These conditions, combined with the obstruction induced by the tree crown, led to lower ventilation in the bottom part of the street canyon, especially during nocturnal hours, and to larger in-canyon volume-averaged air pollutant concentration, i.e., about 20% larger than in the case without trees. Dinoi et al. [58] applied Moderate-Resolution Imaging Spectroradiometer (MODIS) products compared with ground-based measurements of PM_{10} (inhalable particles, with diameters that are generally 10 μm and smaller) mass concentrations, collected over 2006–2008 at two suburban sites. Their results demonstrated the potential of MODIS data for deriving indirect estimates of PM_{10} over southeastern Italy. Other studies were performed in an urban background area (located in the Ecotekne Campus of the University of Salento about 6 km away from the Lecce center), analyzing the seasonal variability of $PM_{2.5}$ (fine inhalable particles, with diameters that are generally 2.5 μm and smaller) and PM_{10} composition and sources in 2013–2016 [59,60], who found that biomass burning was a relevant source with a larger contribution during autumn and winter because of the influence of domestic heating. However, it was not negligible in spring and summer, because of the contributions of fires and agricultural practices. Two soil sources were identified: crustal associated with long-range transport and carbonates associated with local resuspended dust. Both sources contributed to the coarse fraction and had different dynamics, with the crustal source contributing mainly during high winds from the southeast and carbonates contributing during high winds from the north. Other recent studies analyzed, in the same area, the seasonal and diurnal behavior of size-segregated particle fluxes in the period 2016–2018 [61], as well as the influence of African dust advection on fine and coarse particle concentrations, size distributions, and carbon content in 2013–2018 [62], finding that Saharan dust is a relevant source of mineral particles for the Mediterranean region with potential impacts on air quality and climate. Finally, Dinoi et al. [63] performed a long-term characterization of submicron atmospheric particles in the period 2015–2019, where the highest concentrations were observed during autumn–winter.

3. Methodology

3.1. The Investigated District

The district analyzed is called “Santa Rosa”, inhabited by families and numerous students, where three sensitive receptors (a church, a social center, and a soccer field) are present. It is a residential area next to a busy road in the northwest part of the city (Figure 1). The area taken as the “study area” in the district is 300 m × 300 m. The details related to building arrangement and height were acquired through computer-aided design (CAD) files already available for the city. The height and the width of all trees and hedges were measured and/or estimated by comparing them with objects of known height. LAD was estimated for San Pio using an Accu-PAR LP80 ceptometer using the same methodology described in Gatto et al. [52]. The area is characterized by two street canyons, as shown in Figure 1.

3.2. i-Tree Canopy

i-Tree [25] is a collection of urban and rural forestry analysis and benefit assessment tools. It was developed by the United States (US) Forest Service to quantify and value ecosystem services provided by trees, including air pollution removal, carbon sequestration, avoided carbon emissions, and avoided stormwater runoff. Different tools within the i-Tree Suite use different types of inputs and provide different kinds of reports; some tools use a “bottom-up” approach based on tree inventories on the ground, while other tools use a “top-down” approach based on remote sensing data. The tool employed here is i-Tree Canopy, a free web-based application linked to Google Maps, which allows the user to assign different ground cover classes (tree, grass, building, road, etc.) to different portions of the study area. Results provided by the tool concern the ground coverage percentages evaluated through a statistical analysis that defines the standard error (SE) associated with them. Binomial is used as a discrete probability distribution, which is based on the mutual independence of land cover and random sampling of points. The tool, according to the leaf cover area corresponding to the “Tree” class, shows the annual value of air pollutants intercepted by trees (evaluated in g·m/a) and ascribes a monetary value to it (\$/m^2·a). The EPA (US Environmental Protection Agency) defines six pollutants that are estimated by the program: carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and particulate matter (PM), which includes $PM_{2.5}$ and PM_{10}. For further details, the reader is referred to the i-Tree website [25].

In this paper, once the area was defined, the various ground-cover classes were set, i.e., the various types of coverings and urban elements: deciduous and evergreen species, cemented surface (including sidewalks and various cement surfaces, buildings, roads, and any paved surface), grass/herbaceous (although vegetation, the default settings of the model do not consider it as vegetation cover but as a surface), and soil (areas covered by uncultivated land). In total, 847 randomly sampled points were considered within the study area, as shown in Figure 2.

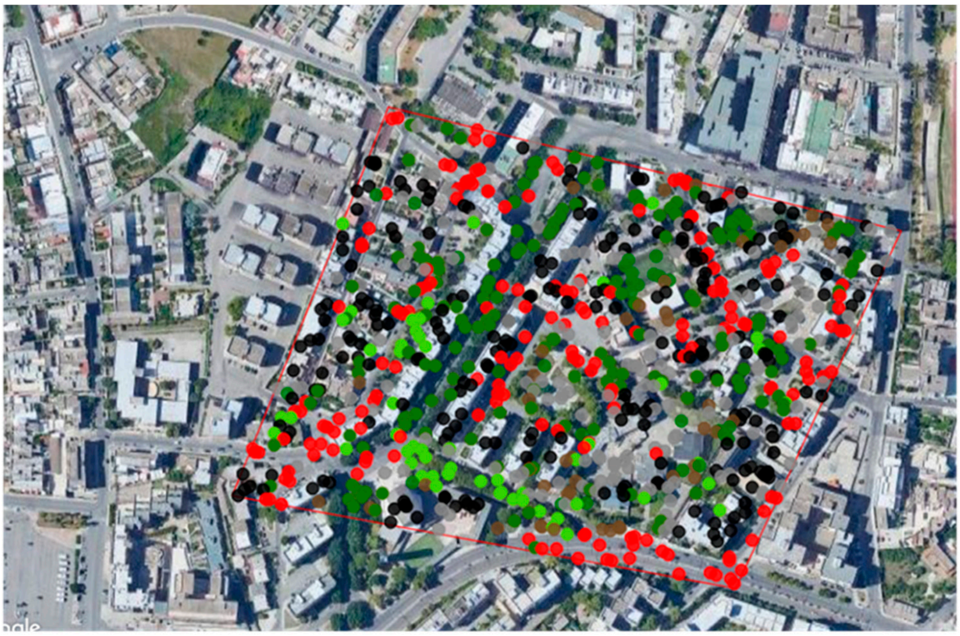

Figure 2. The 847 randomly sampled points within the study area considered in i-Tree Canopy.

3.3. ENVI-Met

With the aim of simulating the effect of urban greening on air quality with high resolution, considering the effects of urban geometry and local meteorology not considered in i-Tree Canopy, modeling simulations were performed using the CFD-based microclimate model ENVI-met [34]. ENVI-met was chosen because of its capability, based on the theory of CFD, to build plant–surface–atmosphere interactions concerning the outdoor environment by using different buildings, various pavement materials, and various vegetation in different configurations. It uses the Eulerian approach to study the dispersion of air pollutants, allowing the simulation of pollutant dispersion including aerosol particles, passive gases, and reactive gases. The Reynolds-averaged Navier–Stokes (RANS) standard k–ε model is used and the dispersion of air pollutants is calculated using the standard advection–diffusion governing equation. The pollution source in ENVI-met can be line, point, or area sources with hourly emission rates. Traffic emissions can be calculated by multiplying an emission factor (g/km·vehicle) with the prevailing traffic intensity (vehicle/s). Vegetation is parameterized using LAD. The presence of vegetation and its influence on atmospheric processes can be simulated by including source/sink terms describing heat, humidity, and momentum in the prognostic equations, although resuspension is not considered. This describes the aerodynamic effect of vegetation and its influence on the deposition of particles and absorption of gases in atmospheric dispersion simulations. In addition to LAD, leaf diameter and a plant type-specific parameter are used to calculate deposition velocity toward ground and leaf surfaces. As a result of gravitational forces, particles deposit on different surfaces, including building walls, roofs, vegetation, and soil, also known as particle sedimentation, which is an acceptable assumption for PM_{10} and $PM_{2.5}$, while other dry deposition processes (Brownian diffusion, impaction, interception) for such particle sizes are neglected. For more information regarding parameters and equations, the reader is referred to Bruse and Fleer [64] and Bruse [65].

In the present study, two scenarios were investigated: a no-vegetation scenario (NOVEG) for comparison and evaluation of the effects of vegetation, and the current scenario with vegetation (VEG). Specifically, the three-dimensional (3D) model area of Santa Rosa district had a dimension of 300 m (x-direction) × 300 m (y-direction) with a vertical height of 60 m. The area, which included buildings and vegetation, was meshed with a grid with resolution of 2 m × 2 m × 2 m, except for the lowest five cells (close to the ground), whose vertical resolution was 0.4 m. To improve model accuracy and stability, five nesting grids (thus 10 m for each side) were also employed to move the model borders far away from the area of interest, since the model does not work reliably at the model borders and at the cells very close to them. Hourly air temperature and relative humidity were forced at the model boundary to drive the simulation by employing the "simple forcing" option; in other words, a forced lateral boundary condition (LBC) was applied for the temperature and the humidity so that the values applied to the model border were taken from the given profile. Cyclic LBCs were set for other variables so that the average conditions upstream of the model area (which produce the inflow profile starting from single values of the variables) were similar to those of the model area. Meteorological data were obtained from a 10 m high ARPA-Puglia (the Regional Agency for Environmental Protection of the Apulia region) station located about 2 km away from the study area. Analyzing the meteorological data for summer 2019, the hottest representative day, 7 July, was chosen with the prevailing wind speed and direction. For each case, ENVI-met was run for a 16 h period, starting at 5:00 a.m. Details of initial and boundary conditions are collected in Table 1.

Table 1. Initial and boundary conditions used in ENVI-met simulations.

Parameter	Definition	Value
Simulation Time	Start date	7 July 2019
	Start of simulation (h)	5:00 a.m.
	Total simulation time	16 h (4 h spin-up + 12 h)
Meteorological conditions	Wind speed	0.9 m/s
	Wind direction	210 °
	Temperature of atmosphere (forced)	Daily profile
	Relative humidity (%) (forced)	Daily profile
Roughness, solar radiation, and clouds	Roughness length	0.1 (urban area)
	Cover of low clouds (octas)	1.00 (clear sky)
	Cover of medium clouds	0.00 (clear sky)
	Cover of high clouds	0.00 (clear sky)
Soil	Initial temperature (K) and relative humidity (%) of upper layer 0–0.2 m	293–50 (default values)
	Initial temperature (K) and relative humidity (%) of middle layer 0.2–0.5 m	293–60 (default values)
	Initial temperature (K) and relative humidity (%) of deep layer below 0.5 m	293–60 (default values)
Computational domain and grid	Grid cells (x, y, z)	150 × 150 × 30
	$\delta x \times \delta y \times \delta z$	2 m × 2 m × 2 m (equidistant: 5 cells close to the ground)
	Nesting grids	5
	Boundary conditions	Cyclic

To represent pollutant sources derived from vehicle traffic, the "traffic" tool was used by setting, as an example, the number of vehicles in the 24 h (8000 vehicles by default for an inner urban road) and the pollutant of interest (as an example, NOx considered as a passive pollutant [15]). The sources were linear, and, to mimic mixing by traffic-induced turbulence, the emission was distributed over the entire dimension of the traffic lane at the height of 0.5 m. The maximum emission rate (at 15:00) was 17.96 ug/m·s, while the emission rate at 7:00 p.m. (hour when the maximum concentration at a selected point was found; see Section 4.3.1) was 14.11 ug/m·s. Traffic distribution and source locations are shown in Figure 3.

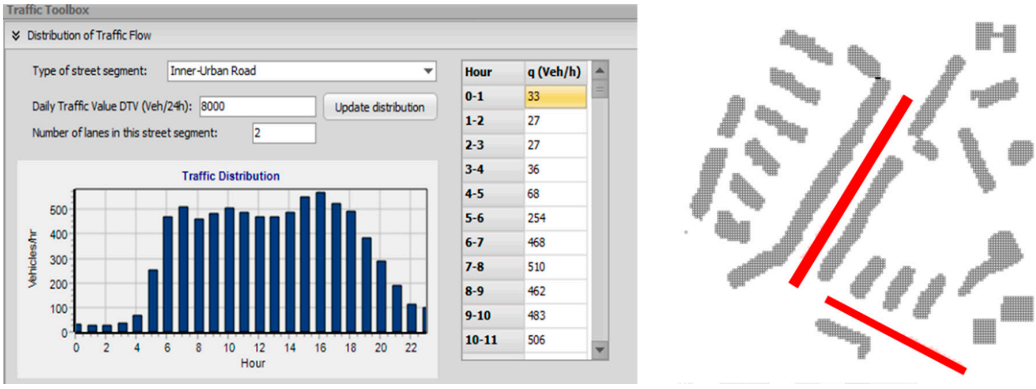

Figure 3. Left: screen of traffic toolbox in ENVI-met with details of default traffic distribution during the day. Right: the linear sources located in the street canyons (red rectangles).

4. Results

4.1. Morphological and Vegetational Characterization of the District

The two street canyons shown in Figure 1 are characterized by buildings with an average height of 15 m and an aspect ratio (building height/street width ratio, H/W) of 0.6. Street canyon "a" is 172 m long and has two side rows of 20 trees of *Quercus ilex* L. subsp. *ilex* (evergreen species), with an average height of 10 m, a 5 m high and wide crown, and an LAD of 0.71 m^2/m^3. Street canyon "b" is more open and 118 m long; it is characterized by a central row of *Tilia* sp. (deciduous species) with an average height of 15 m, a 6 m high and 7 m wide crown, and an LAD of 1.00 m^2/m^3. The area has a great variety of vegetation (Figure 4 shows the most abundant species); an aggregate of trees is present on Piazza Santa Rosa (including *Pinus halepensis* Mill., *Prunus armeniaca* L., and *Ceratonia siliqua* L., *Pittosporum tobira* (Thunb.) W.T. Aiton). Moreover, in Via Adige (avenue parallel to street canyon "a"), there is a row of *Cercis siliquastrum* L. subsp. *siliquastrum* (a deciduous species known as the Judas tree) and several trees of *Pinus halepensis* Mill. and *Quercus ilex* L. subsp. *Ilex*, also arranged in rows. One tree of *Platanus hispanica* Mill. ex Münchh. stands out in Via Adige (deciduous species) with a height of 17 m and one tree of *Grevillea robusta* A. Cunn. ex R.Br.

Air Pollution Reduction Potential of the Identified Species

Several studies on the impact of vegetation on air quality led to the identification of appropriate species to mitigate air pollution problems in urban environments. Among these, Sicard et al. [66] classified species according to their ability to remove O_3, NO_2, and PM_{10} and to emit BVOCs. In their method, each species was assigned an index called the species-specific air quality index (S-AQI), ranging from 1 to 10 (from "recommended" (>8) to "not recommended" (<4)). The indices calculated by Sicard et al. [66] are reported below for each species identified in the study area.

Quercus ilex L. subsp. *ilex* is the species present in greatest quantity, characterizing street canyon "a" (Figure 5, top). Although this species is very suitable and widely used in urban avenues probably because it is very resistant to drought and air, the literature shows that it is not among the species recommended to decrease the concentration of air pollutants. According to Sicard et al. [66], the AQI is 3.6 (<4: not recommended) mainly due to high emissions of BVOCs [67] and pollen [68]. However, the physical characteristics of *Quercus* pollen grains give them a relatively short dispersion capacity [67]. Regarding the ability to reduce air pollutants, the removal effect is reduced for O_3 and moderate for NO_2 and PM_{10} [69]. In a study conducted in the city of Terni, Sgrigna et al. [70] evaluated the deposition effect by quantitatively analyzing, for three periods of the year, the fractions of $PM_{2.5}$ and PM_{10}. The average value of PM deposition on leaves was 20.6 μg/cm^2. However, the information on this species is still limited, and there is no information on aerodynamic effects. From a microclimatic and thermal comfort point of view, *Quercus* spp. provide shade and contribute to improving the local microclimate and thermal comfort [52,71].

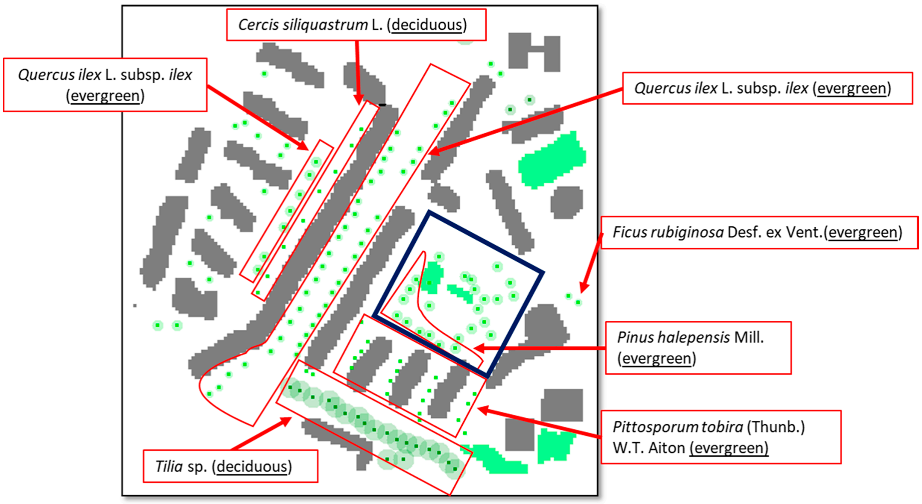

Figure 4. Most abundant plant species present in the Santa Rosa district. The blue rectangle indicates Piazza Santa Rosa.

Figure 5. Top: *Quercus ilex* L. subsp. *ilex* in street canyon "a". Bottom: *Pittosporum tobira* (Thunb.) W.T. Aiton and *Tilia* sp. in street canyon "b".

Tilia sp. in street canyon "b" (Figure 5 bottom) is very effective for the removal of air pollutants. The AQI is equal to 7.1 because of its high potential absorption rate of gaseous pollutants and its ability to capture particles, together with a low rate of BVOC emission and ozone formation. Moreover, from a thermal comfort point of view, *Tilia* sp. is a highly recommended species [52,72].

Ceratonia siliqua L. has an AQI of 5.6 with a moderate effect on air pollutant sequestration and a low BVOC emission rate. This index is probably low, however, due to the scarcity of information in the literature. According to Blair et al. [73], it is one of the most capable species in carbon sequestration per year (17.5 kg/a). Given its characteristics, also considering its positive effect on thermal comfort [52], and it being a very widespread Mediterranean species, it can be considered a recommended species in the urban environment.

Cercis siliquastrum L. subsp. *siliquastrum*, despite the scarcity of information in the literature, has an AQI of 6.5 which is probably very much affected by the high BVOC emission rate and moderate O_3 potential formation [66]. However, it is among the recommended species because, in addition to the moderate potential for absorption of dust and gaseous substances, it is particularly suitable for urban trees, with resistance to air pollution and drought.

Although *Pinus halepensis* Mill. is a widespread species in urban environments, it has no environmental value from the point of view of air pollutant removal. According to Sicard et al. [66], the AQI is 4.1 with limited potential to reduce O_3, NO_2, and PM_{10} and moderate BVOC emission.

Another species strongly penalized by BVOC emission rates, despite its high absorption rates of air pollutants, especially NO_2 [66] and CO_2 [74], is the *Platanus hispanica* Mill. ex Münchh. A single tree is present in Piazza Santa Rosa. Since its AQI is 6.2, with it being very widespread in Italy and considering its resistance to stress from drought and air pollution, it can be considered a recommended species in the urban environment.

Finally, the presence of only one tree of *Prunus armeniaca* L. in the district should be noted. According to Sicard et al. [64], it is among the recommended species with an AQI of 9.1 with a high absorption potential of O_3, NO_2, and PM_{10}.

4.2. i-Tree Canopy: Cover Classes, Potential Air Pollutant Removal, and Economic Benefits

Figure 6 shows the percentages of ground cover with their standard errors (SE). The characterization shows that evergreen species are present in greater number (18.77%) than deciduous species (6.38%). In total, the green cover is equal to 25%. The data referring to buildings and asphalt cover are consistent, being an urban district. A first analysis shows that the cemented area has a coverage percentage of 18.54%, almost equal to the area occupied by evergreen species.

Table 2 shows a rough estimate of economic benefits obtained from i-Tree Canopy in terms of the amount of air pollutants (in pounds (lb)) removed annually with a maximum value corresponding to the storage expressed in tons (t) of CO_2 in the trees. The considered scenario is the current one, i.e., with the vegetation present in the study area. It is possible to notice that the benefits obtained from carbon sequestration and storage alone far outweigh the benefits obtained from the removal of all other air pollutants. This is due to the fact that vegetation needs CO_2 to carry out photosynthesis; thus, plants during growth store large amounts of carbon in the biomass, functioning as "carbon sinks" [75]. This also indicates that vegetation is potentially a poor mitigation tool for air pollution. It should be underlined that the estimation of i-Tree Canopy neglects plant species, their physical characteristics, conditions, exposure, local meteorology, and the presence of buildings. The cover classes are detailed for greater clarity in the estimation of percentages, but the tool only considers the distinction "tree" and "not tree" and, therefore, only the total amount present.

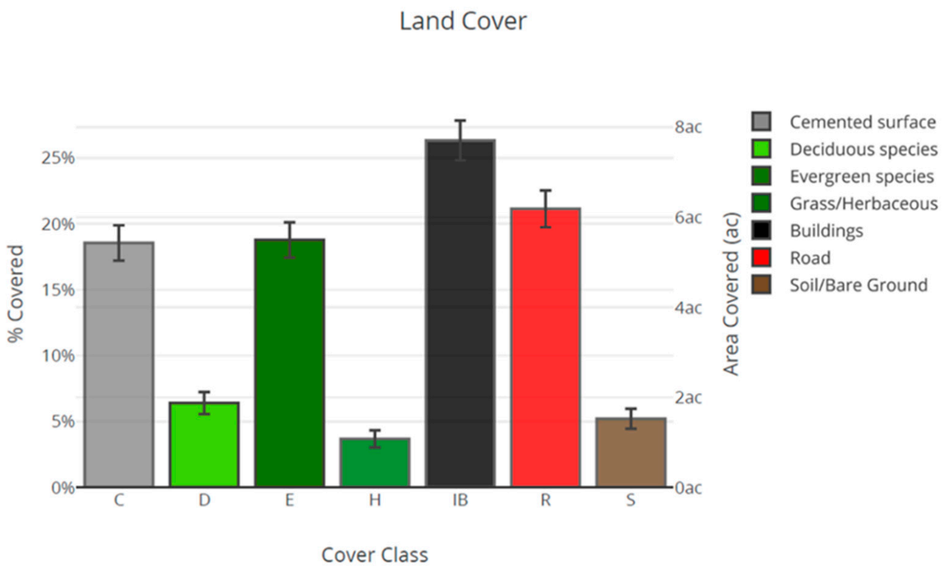

Figure 6. Details of cover classes with their respective cover percentages (from i-Tree Canopy report).

Table 2. Economic benefits of CO_2 storage (expressed in tons) and removal of air pollutants by trees (from i-Tree Canopy report).

Tree Benefit Estimates: Carbon (English Units)						
Description	**Carbon (t)**	**±SE**	**CO_2 Equivalent (t)**	**±SE**	**Value (EUR)**	**±SE**
Sequestered annually in trees	10.05	±0.60	36.86	±2.19	1586	±94
Stored in trees (Note: this benefit is not an annual rate)	252.48	±14.97	925.75	±54.88	39,822	±2361

Tree Benefit Estimates: Air Pollution (English Units)					
Abbreviation	**Description**	**Amount (lb)**	**±SE**	**Value (EUR)**	**±SE**
CO	Caron monoxide removed annually	8.32	±0.49	5	±0
NO_2	Nitrogen dioxide removed annually	45.97	±2.72	9	±1
O_3	Ozone removed annually	355.07	±21.05	427	±25
PM_{10}	Inhalable particles, with diameters that are generally 10 µm and smaller, removed annually	100.78	±5.97	292	±17
$PM_{2.5}$	Fine inhalable particles, with diameters that are generally 2.5 µm and smaller, removed annually	18.14	±1.08	893	±53
SO_2	Sulfur dioxide removed annually	22.60	±1.34	1	±0
Total		550.87	±32.66	1,627	±96

Note: carbon sequestered is based on 1365 t/ac/year. Carbon stored is based on 34,281 t/ac. Carbon is valued at 43.02 EUR/t. Air pollution estimates are based on the following values in lb/ac·year–EUR/lb·year: CO, 1130–0.62; NO_2, 6.241–0.20; O_3, 48.211–1.20; PM_{10}, 13.683–2.90; $PM_{2.5}$, 2.463–49.23; SO_2, 3.068–0.06 (English units: t = tons (2000 pounds), lb = pounds, ac = acres).

4.3. ENVI-Met: Flow and Dispersion of Air Pollutants

4.3.1. Profiles

Figure 7 shows the hourly profiles of NOx concentration, wind velocity, and turbulent kinetic energy (TKE) calculated at pedestrian height at points P1 (street canyon "a") and P2 (street canyon "b"). For all the scenarios in street canyon "a", the concentration during the day is lower than that in the late afternoon. The valley and peak occur at 1:00 p.m. (VEG: 29.55 µg/m^3; NOVEG: 15.40 µg/m^3) and 7:00 p.m. (VEG: 56.97 µg/m^3; NOVEG: 37.34 µg/m^3), respectively. The valley shows a "U" shape, which means that the NOx concentration is maintained at a relatively lower level within 3–4 h. It is interesting to note that, at 3:00 p.m., the concentration is still low although the emission rate was maximum. This is because the higher wind speed and TKE during the day (associated also with higher temperatures, not shown here) cause the pollutant to disperse more rapidly. In street canyon "b", the hourly profiles of concentration, wind speed, and TKE are sharper, with a higher concentration at 3:00 p.m. (VEG: 20.43 µg/m^3; 18.10 µg/m^3) mainly associated with a larger TKE.

It is evident that, in both street canyons, the vegetation scenario experiences higher concentrations than those found in the no-vegetation scenario. The effect of the presence of urban greening is more significant in street canyon "a", where the concentration increase is about 90% during the late morning (up to 3:00 p.m.) and about 50% at 7:00 p.m., while, in street canyon "b", the concentration increase is about 30% during the morning and mid-afternoon, and it decreases to about 10% or less at 3:00 p.m. and in the late afternoon. Finally, the NOx concentration in street canyon "a" is, in general, higher than in street canyon "b", and this is likely due to the longer street (and, thus, line source) with the emission rate being the same for both street canyons.

4.3.2. Maps

Figure 8 shows the air pollutant concentration maps at 3:00 p.m. (when the maximum concentration was found at point P2) and at 7:00 p.m. (when the maximum concentration was found at point P1) at pedestrian height. Comparing the spatially averaged canyon concentrations, in accordance with the results obtained and discussed at points P1 and P2, higher values are found in street canyon "a". Furthermore, the concentration increases in the vegetation scenario. This increase is more marked in street canyon "a" (about 70% at both 3:00 p.m. and 7:00 p.m.) compared to street canyon "b" (about 20% at 3:00 p.m. and 24% at 7:00 p.m.). Results are consistent with the findings from Di Sabatino et al. [57], as discussed in Section 2.

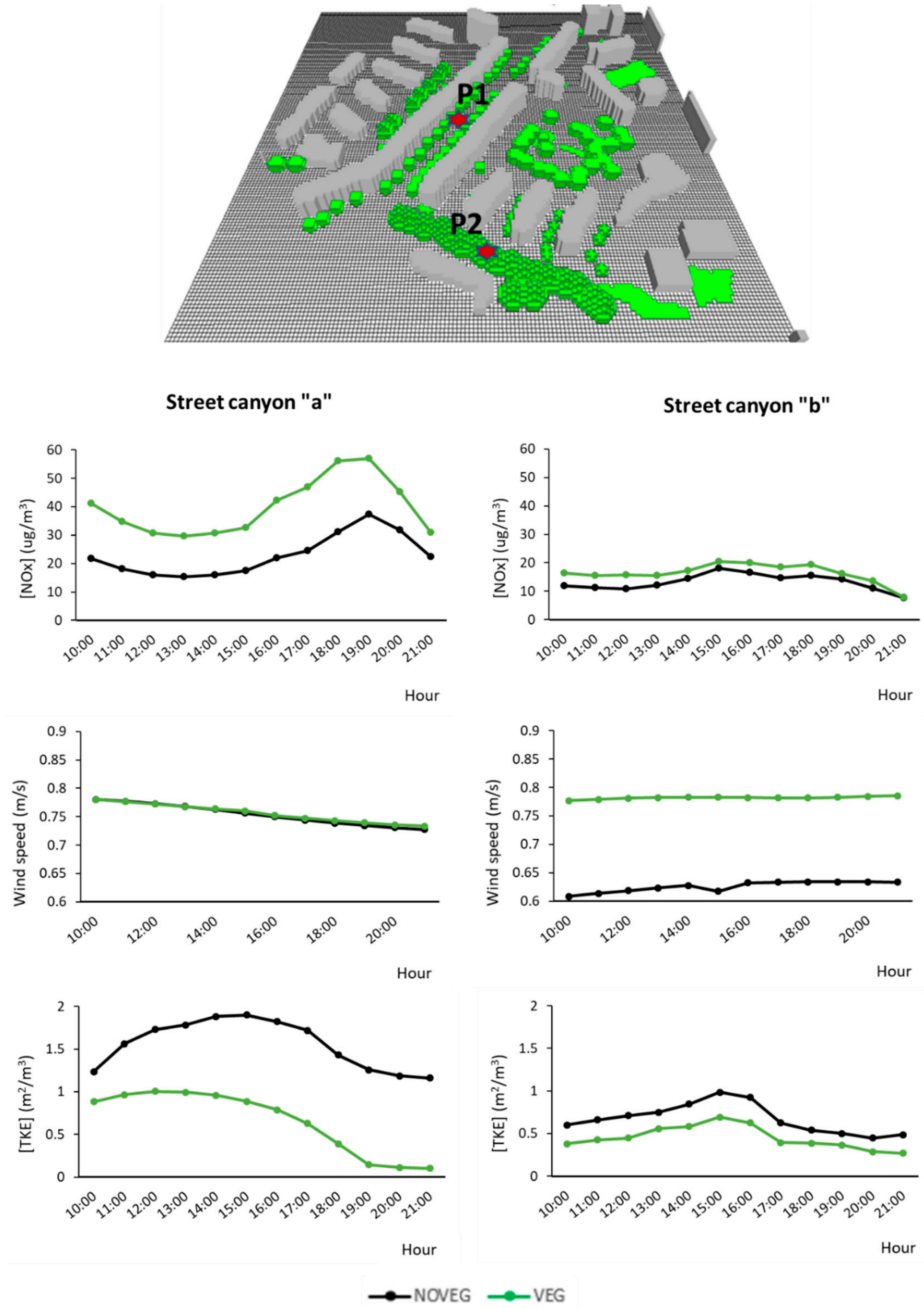

Figure 7. Top: extraction points P1 (street canyon "a") and P2 (street canyon "b"). Hourly profiles of NOx concentration, wind velocity, and turbulent kinetic energy (TKE) obtained from ENVI-met on 7 July 2019 for the scenario without vegetation (NOVEG) and the current one with vegetation (VEG) in street canyons "a" and "b".

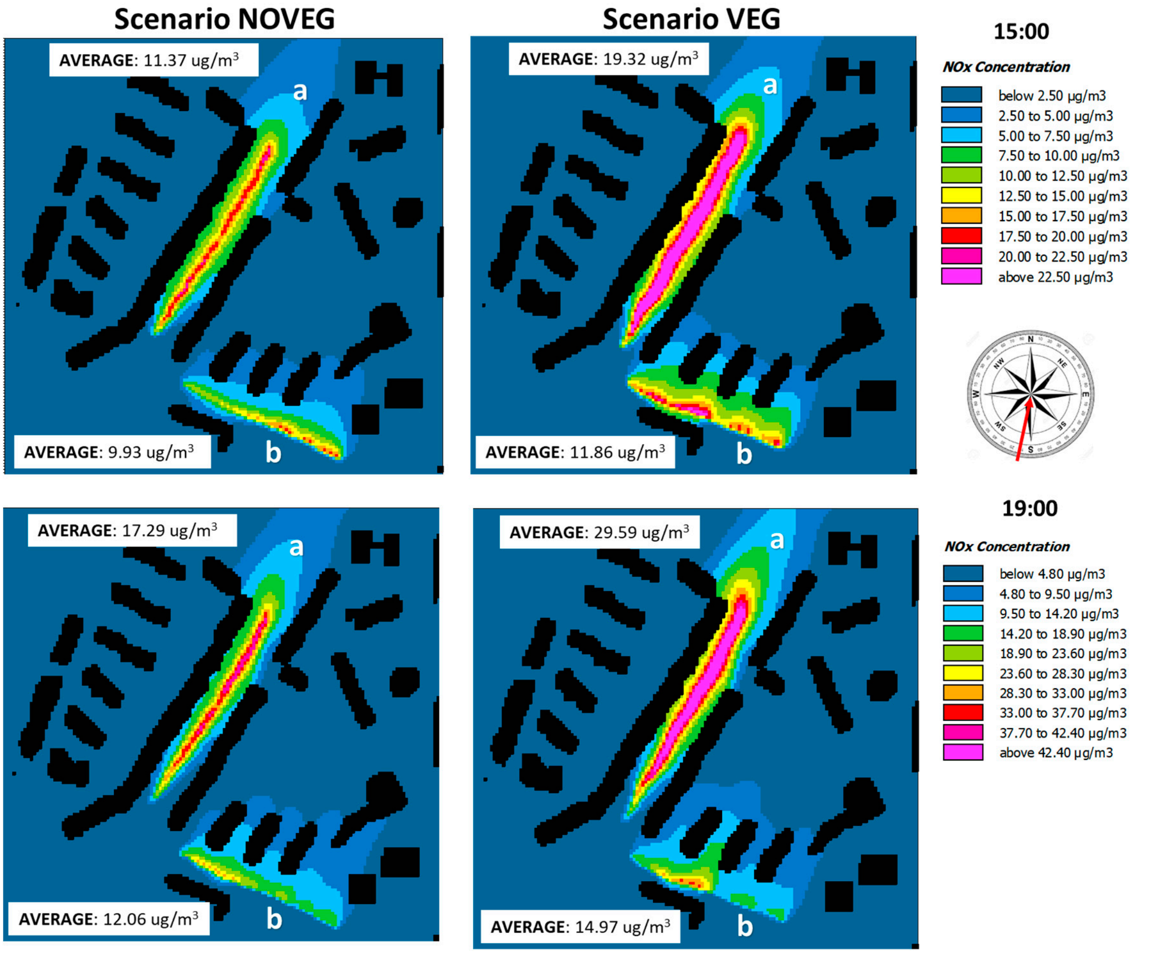

Figure 8. NOx concentration maps obtained from ENVI-met at 3:00 p.m. on 7 July 2019 at pedestrian height for the scenario without vegetation (NOVEG) and with vegetation (VEG) in street canyons "a" and "b", with indication of the spatially averaged canyon concentrations. The wind rose indicates the wind direction (red) of 210°.

5. Discussion and Conclusions

5.1. Integrated Analysis of Results

The software i-Tree Canopy and the CFD microclimate model ENVI-met were simultaneously employed in a preliminary analysis of the effect of urban greening on air pollutant dispersion, CO_2 sequestration, and economic benefits in a district located in the city of Lecce. The district is characterized by two street canyons with different characteristics such as the following:

- Species and their arrangement: two rows of *Quercus ilex* L. subsp. *ilex* in street canyon "a" and one row of *Tilia sp.* in street canyon "b";
- Geometry of the canyon: street canyon "a" is delimited by buildings on both the right and the left sides, while street canyon "b" is more open;
- Wind direction: parallel to street canyon "a" axis and perpendicular to street canyon "b" axis.

From the analysis of the results, the difference in functionality and potential between i-Tree Canopy and ENVI-met is clear for the evaluation of the effects of urban greening. i-Tree Canopy allowed obtaining data related to CO_2 storage, air pollutant removal, and economic benefits of the whole district considering the total amount of vegetation in the area. The power of this tool is linked to its ability to define the study area using a satellite map and to assign different ground-cover classes to different portions of the study area. However, the predicted air pollutant removal discussed in Section 4.2 is only potential, giving an estimation of the expected benefits of the whole vegetation without considering its characteristics (shape, species, arrangement), as well as its interaction with meteorological and geometrical factors of the area [24]; furthermore, the emission sources were calculated from default values generally valid for an urban environment.

With the vegetation planted in street canyons, an in-depth study of the interaction among individual buildings, meteorology, and plants was possible using ENVI-met, which allowed entering, in detail, the emissions of different pollutants, fully simulating the physical factors of plants, such as photosynthesis and its effects, and considering the absorption of air pollutants. The analysis showed that, in the presence of trees in street canyon "a" (two rows of *Quercus ilex* L. subsp. *ilex*), the air pollutant concentration at pedestrian height was always higher in the presence of vegetation. In street canyon "b" (one row of *Tilia sp.*), the effect was not as evident as that in street canyon "a". This larger increase in street canyon "a" was due to different factors, such as the following:

- A lower absorption effect of the species *Quercus ilex* L. subsp. *ilex* in canyon "a" due to a lower LAD (0.71 m^2/m^3) than *Tilia sp.* (1.00 m^2/m^3);
- Larger aerodynamic effects, i.e., a relatively higher "blockage" effect, caused by two rows of *Quercus ilex* L. subsp. *ilex* in street canyon "a" compared to one row of *Tilia sp.* in the more open street canyon "b". This was mainly confirmed by the larger decrease in turbulent kinetic energy. This larger aerodynamic effect in street canyon "a" occurred even though the wind was parallel to the street axis, while, in street canyon "b", it was perpendicular (the latter is usually considered the worst scenario with respect to air pollutant dispersion [76]).

Results confirm what is already found in the literature regarding the influence of vegetation on the reduction of ventilation, i.e., the trapping effect of air pollutants in the presence of vegetation may reduce the air exchange between the inside and outside of the canyon, especially below the canopy [14,16,20]. The impact of vegetation on air quality is highly context-dependent, with models suggesting that it can improve urban air quality in some situations but be ineffective or even unfavorable in others. The practical design implications of the results found in the literature are still too limited to provide general guidelines for urban vegetation management, as their relevance is usually restricted to the investigated location [77].

5.2. Future Perspectives

Future studies in the investigated district may, for example, address the development of new scenarios in ENVI-met in which plant species can be substituted to assess and improve their positive effect on air pollutant dispersion and accumulation. Recently, the Life GAIA project [78], promoted by the Municipality of Bologna, together with Cittalia-Fondazione Anci Ricerche, Impronta Etica, Istituto di Biometeorologia-CNR and Unindustria Bologna, also led to the identification of some species of trees with a higher potential to deposit/absorb air pollutants and a lower allergenic risk, by analyzing the following ecophysiological characteristics: CO_2 absorption, potential particle capture, potential absorption of gaseous pollutants, BVOC emissions, and potential O_3 formation. Cross-referencing the results from Sicard et al. [66] and Life GAIA [78], effective species in the removal of air pollutants by deposition/absorption which could be tested in the district (apart from those already present; see Section 4.1) are *Acer* sp., *Ailanthus altissima* (Mill.) Swingle, *Carpinus* sp., *Cedrus* sp., *Crataegus* sp., *Fagus sylvatica* L., *Liriodendron tulipifera* L., and *Prunus* sp. Please note that *Cedrus* sp., despite its very high air pollutant removal potential, due to its size (25–30 m high), is not considered suitable for planting near houses or along avenues due to the risk of falling. Among medium-sized trees and low-growing plantations, i.e., *Acer* sp., *Crataegus* sp. and *Prunus* sp., both *Acer* sp. and *Prunus* sp. are among the 10 most numerous tree species frequently found in cities around the world [79]. The species *Celtis australis* L. is also suitable for urban avenues and very recommended because, with a moderate effect of absorption and reduction of air pollutants, it has a very low BVOC emission rate and an excellent tolerance to drought, parasites, and diseases [68]. However, it should be stressed that the potential of urban trees related to air pollutant removal also depends on multiple stress factors to which they can be exposed such as soil volume, the space between one individual and another, soil type, and air pollution [80].

In addition to testing the planting of new species, other meteorological conditions (in terms of wind direction and wind speed) may be tested to investigate in detail the influence of these factors on air quality. New i-Tree Canopy scenarios will allow evaluating the effect on economic benefits by increasing or decreasing the percentage of vegetation cover. A step toward the employment of i-Tree suite is the use of i-Tree Eco, which is a flexible software application designed to use data collected in the field from single trees, complete inventories, or randomly located plots throughout a study area along with local hourly air pollution and meteorological data to quantify forest structure, environmental effects, and value to communities [25]. This tool requires specific data related to vegetation, meteorology, and air pollution concentrations, and it will be explored for the case of Lecce to check its potential and complementarity with CFD tools such as ENVI-met.

We expect that this approach employing two tools can be explored in similar scenarios in other cities and that the findings provide urban planners and policymakers with options for designing urban greening. In this regard, such an approach can be useful to put in practice the novel conceptual framework recently proposed by Hewitt et al. [24], which should help to prioritize green infrastructure interventions when intended for air quality benefits and indicate which investment decisions should be supported by more detailed modeling studies.

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