23rd International Conference on
Harmonisation within Atmospheric Dispersion Modelling
for Regulatory Purposes
15-19 September 2025, Hamburg, Germany

EXTENDED ABSTRACT

Integrating Nature-Based Solutions into Citywide Air Quality Reconstruction at Microscale

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Introduction

Urban air quality is strongly influenced by local morphology, meteorological variability, and the spatial distribution of emission sources—especially in dense environments such as road networks and street canyons. In recent years, Nature-Based Solutions (NBS**)** such as urban greening and tree planting have emerged as promising strategies to mitigate air pollution and improve microclimate conditions in cities [1]. However, their net impact on pollutant concentrations is complex: vegetation can enhance removal through dry deposition, but may also reduce ventilation and trap pollutants near sources.

Assessing these effects requires modeling tools capable of resolving dispersion processes at the microscale (1–10 m), which is beyond the capabilities of conventional mesoscale models [2]. To address this challenge, we present a citywide modeling framework that reconstructs annual mean pollutant concentrations at high spatial resolution by convolving precomputed dispersion kernels, allowing rapid, process-based evaluation of NBS interventions.

The framework is model-agnostic, computationally efficient, and applicable to entire urban domains. In a real-world application to the metropolitan area of Taranto (southern Italy), dispersion kernels were generated using the PMSS (Parallel Micro-SWIFT-SPRAY) modeling system [3,4] from normalized traffic emissions under a set of classified meteorological conditions. NBS effects are incorporated through two key mechanisms—aerodynamic drag and dry deposition—parameterized using spatially varying attributes such as tree height, canopy density, and leaf type. Both effects are applied directly to the dispersion kernels in a spatially explicit manner, enabling fast and realistic assessment of NBS impacts on urban air quality.

Materials and Methods

Microscale dispersion kernels

Dispersion kernels were computed using the PMSS (Parallel Micro-SWIFT-SPRAY) modeling system in steady-state mode for a discrete set of meteorological classes. Each class is defined by a combination of the following variables:

- **wind direction** at 10 m (8 bins: 0°, 45°, …, 315°),
- **wind speed** at 10 m (6 values: 1, 2, 3, 5, 7, 9 m/s), and
- **atmospheric stability**, classified into 5 Pasquill classes (A–E/F).

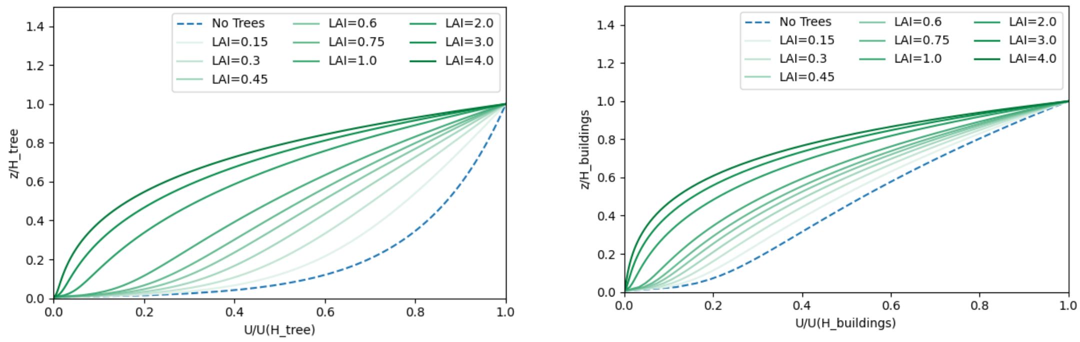
Normalized traffic emissions were used to isolate the dispersion response driven by urban form. Wind input profiles followed a power-law, with exponents depending on stability. For each meteo class, PMSS was run to simulate ground-level concentration fields over a 2 km buffer surrounding each road segment, which acted as an individual line source. The road network, derived from OpenStreetMap, covers the entire urban domain. Each kernel is location-specific, since urban morphology—including building footprints and heights—was explicitly included in the PMSS input. This enables the kernels to account for local-scale flow modifications such as channelling and recirculation within street canyons.

In the convolution phase, kernels are selected hourly for each emission source based on large-scale meteorological input (10 m wind speed/direction and stability). Each kernel is scaled by the corresponding traffic emission at that time step, and convolved over the domain. The resulting hourly maps are then temporally aggregated to obtain annual or seasonal mean concentrations. This approach ensures high spatial detail while remaining computationally efficient over long time periods. For the application on the Taranto area, traffic emissions were spatially distributed over a road network derived from OpenStreetMap and modeled using a bottom-up approach based on local traffic counts and fleet composition, implemented via the COPERT5 methodology [4]. Meteorological input for the year 2023 was provided by 1-km WRF simulations.

Parametrization of NBS aerodynamic effect

The aerodynamic effect of vegetation is incorporated into the kernel framework by modifying the dispersion fields as a function of vegetation structure and local urban form. Two distinct configurations are considered: in open areas without buildings, trees are treated as a sparse canopy that alters the vertical wind profile through drag forces, parameterized as a function of the Leaf Area Index (LAI); in this case, the profile is reshaped according to an analytical formulation [6], as shown in Figure 1, left. In contrast, when vegetation is located within street canyons, trees interact with both the flow and the surrounding buildings, leading to a vertical compression of the wind profile at lower levels [7] (Figure 1, right). In this canyon configuration, additional geometric parameters such as canyon depth (H/W) and street–wind angle significantly influence the extent of the aerodynamic impact. In both cases, the wind speed reduction is computed by integrating the modified profile (for a given LAI) and dividing it by the integral of the reference profile without vegetation. In the convolution framework, the resulting scaling factor is then applied to the driving wind speed for the selection of dispersion kernels to account for the aerodynamic effects of Nature-Based Solutions in a spatially explicit manner.

Figure 1. Vertical wind speed profiles for different values of LAI. (left) sparse canopy case, normalized with tree height. (right) street canyon case normalized with buildings height, with wind parallel to road and canyon depth H/W = 4/3.



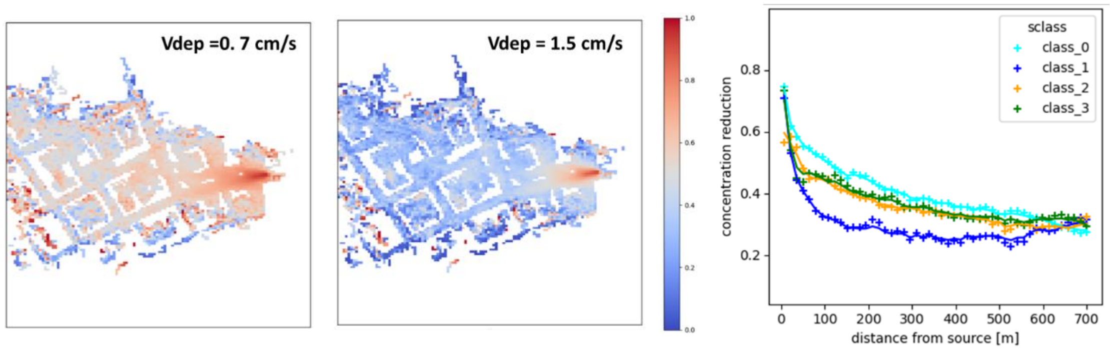
Parametrization of NBS dry deposition effect

Dry deposition removes airborne pollutants by transferring them to surfaces, with efficiency described by the deposition velocity v_d. This velocity depends on LAI, leaf type, seasonality, meteorological conditions, and—especially for particulate matter—on particle diameter [8,9]. To account for the effect of deposition on pollutant concentrations, we derived empirical reduction functions based on PSPRAY steady-state simulations. These were performed for a range of classified deposition velocities and for all meteorological classes used in the kernel generation. Simulations were run on four representative road segments, selected from distinct urban contexts identified via K-Means clustering based on built-up fraction, buildings count and buildings height within a 500 m buffer. The resulting clusters correspond to distinct urban configurations: Class 0 includes sparse, low-rise buildings in peri-urban or agricultural areas; Class 1 features dense and tall buildings typical of the city center and industrial zones; Class 2 groups compact, low-rise residential areas; and Class 3 represents moderately built environments found in peripheral districts.

Figure 2 summarizes the simulation results: the left panel shows concentration reduction fields for Class 2 under a specific meteorological condition and two deposition velocities; the right panel reports the radial reduction factor as a function of distance for a fixed deposition velocity across all clusters.

The core reduction factor is expressed as $R(d) = \frac{e^{-\alpha d}}{(1+\beta d)^{\gamma}}$ where d is the distance from the source and α, β, γ are fitted parameters. However, to account for the actual vegetated surface available for deposition, an additional multiplicative term is applied. The final reduction factor applied to the dispersion kernel becomes $R(d) = \frac{e^{-\alpha d}}{(1+\beta d)^{\gamma}} exp\left[(1 - LAI)\frac{v_d}{U}\frac{d}{h}\right]$, where h is the average tree height, and U is the average advection velocity of the plume. This correction ensures that the reduction effect is weighted according to the effective deposition surface, proportional to the projected vegetated area (i.e., LAI times grid-cell base area), and modulated by transport conditions.

Figure 2. (left) Concentration reduction fields for urban Class 2 for different deposition velocities and meteo conditions: wind speed at 10 m 1 m/s, wind direction 90°, stability E. (right) Concentration reduction as a function of distance for $v_d = 0.7\ m/s$, LAI = 1 and the same meteo of left panel.



Results and Discussion

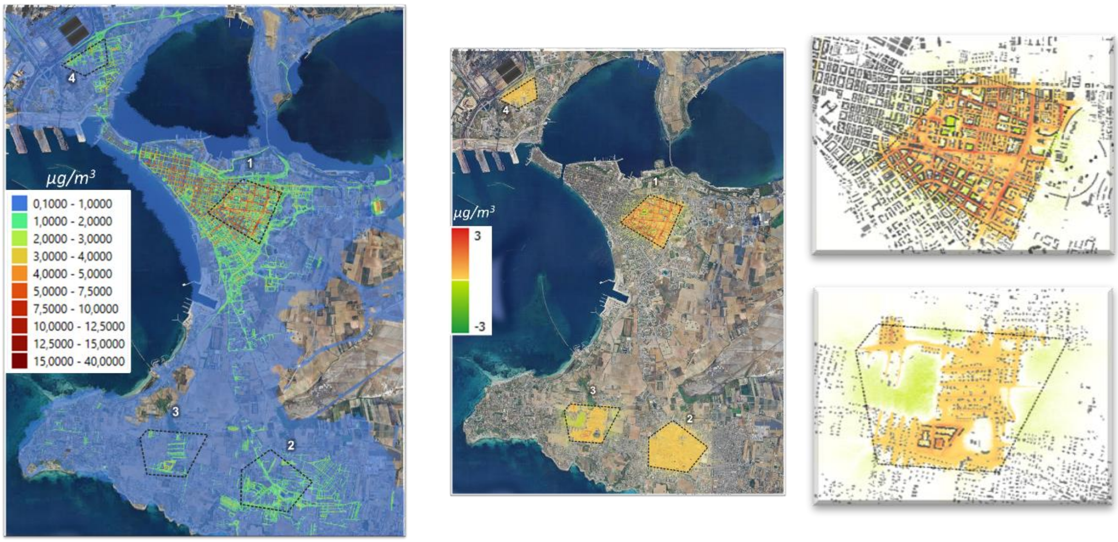
The modeling framework was applied over the urban area of Taranto (9 × 12 km at 5 m resolution). To evaluate the impact of Nature-Based Solutions (NBS), four test areas were identified across the city, each characterized by different vegetation attributes: average tree height, leaf type (broadleaf or needleleaf, evergreen or decicuous), and tree spatial density. From these attributes, the Leaf Area Index (LAI) was derived [8]. Details for each area are reported in Table 1.

Table 1: Attributes of each NBS test area

NBS Zone	Leaf type	Trees density [%]	Trees height [m]
1	Evergreen Needleleaf	50	10
2	Deciduous Broadleaf	50	10
3	Evergreen Needleleaf	50	10
4	Deciduous Needleleaf	80	10

For every hour of 2023 and for each emission source within the NBS areas, wind speed was rescaled to account for aerodynamic drag based on local LAI and tree height. The corresponding dispersion kernel was selected accordingly and rescaled to include the effect of dry deposition. Figure 3 summarizes the annual mean PM_{10} concentrations. The left panel shows the spatial distribution across the domain; the center shows the difference between scenarios with and without NBS; the right panel zooms into two sub-areas with similar vegetation.

Figure 3. (left) Annual PM_{10} concentration mean computed in the kernel convolution framework. (center) PM_{10} concentration difference between the case with NBS and without NBS. (right) Close-up of the PM_{10} concentration difference around NBS zone 1 and NBS zone 3.



The combined impact of aerodynamic and deposition effects can result in either a net increase or decrease in concentration; however, the overall magnitude of the effect is generally limited and not dramatic in absolute terms. The response is not linear, but strongly dependent on the configuration of NBS attributes. Typically, aerodynamic drag dominates near sources, leading to local accumulation, while dry deposition becomes more relevant at greater distances, particularly in high-LAI areas.

As illustrated in Figure 2, urban morphology significantly influences the spatial extent of deposition. In dense urban configurations (Class 2), deposition appears more effective at shorter distances due to increased pollutant residence time caused by complex flow paths.

In conclusion, the framework supports harmonized, high-resolution assessment of vegetation-related air quality effects, offering a flexible and efficient tool for urban planning applications.

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