XII giornata sulla modellistica in aria(net)
Milano, 26 marzo 2025

Natural Based Solutions modelling in Urban Environment

Application on the city of **Taranto** in the context of **CALLIOPE** project

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Natural based solutions modelling

We model two antagonist effects of natural based solutions on concentration in an urban context

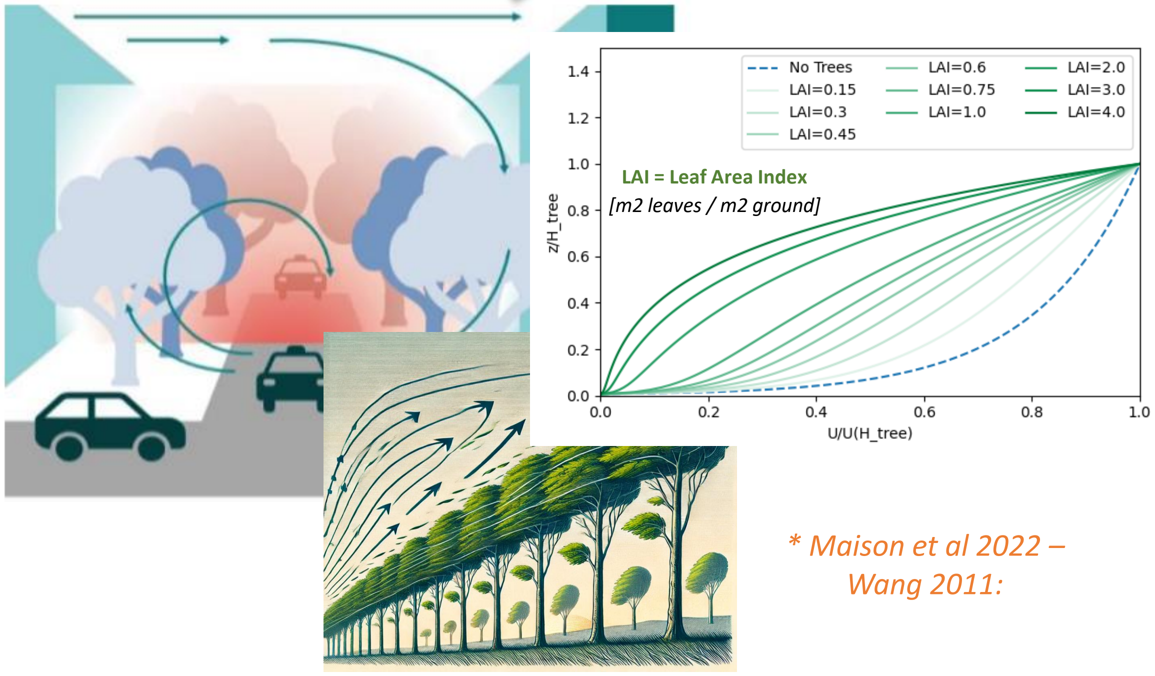
Aerodynamic effect

The presence of trees modifies the wind profile, reducing on average the wind speed

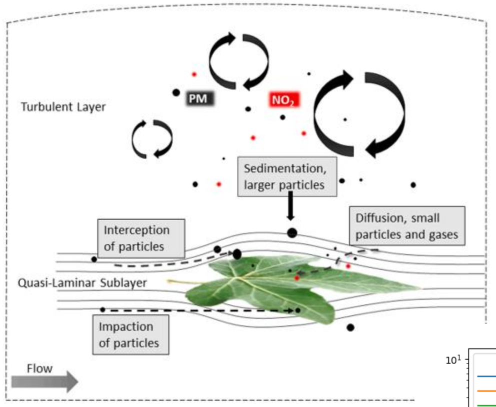
The net effect is an **increase of the concentration**

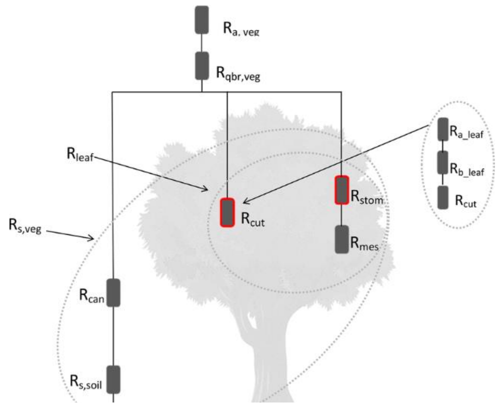
Dry deposition

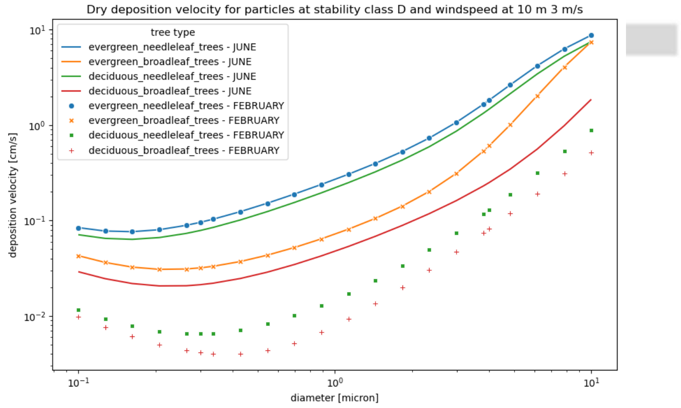
The deposition of pollutants on the leaf cover removes some mass from the atmosphere, **reducing the concentration**



** Maison et al 2022 – Wang 2011:*





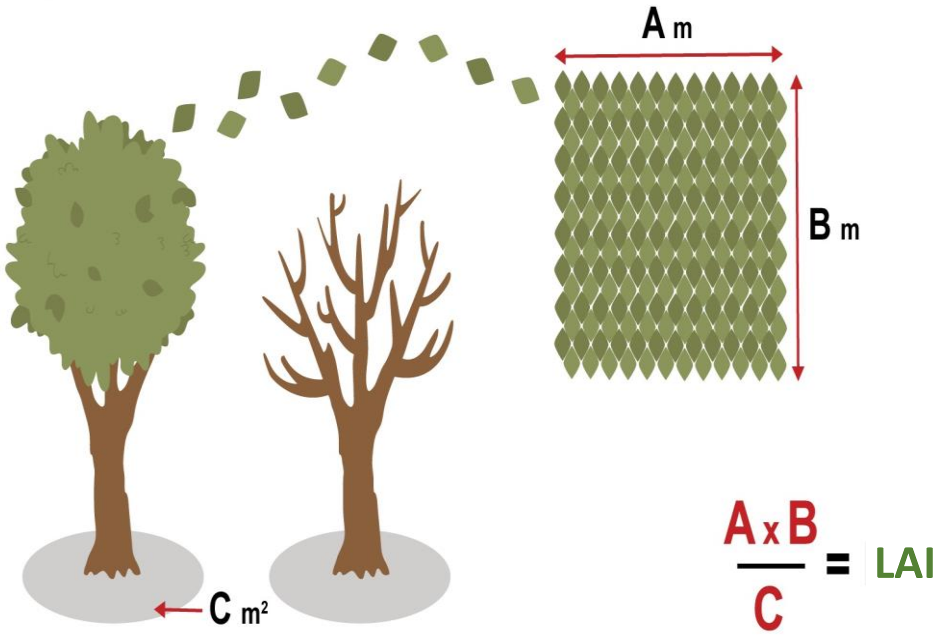


** Linden et al 2023 – Petroff et al 2010 – Zhang 2001/2003*

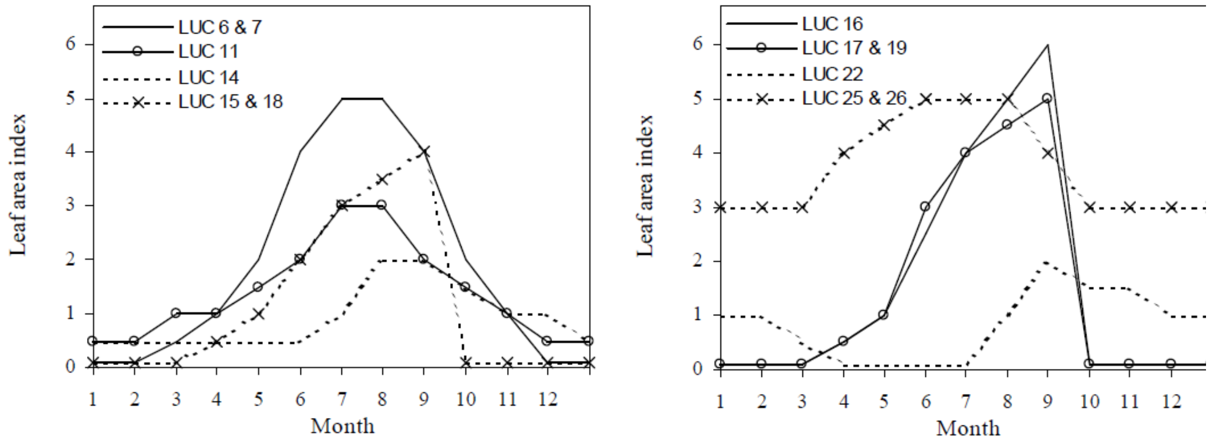
Leaf Area Index

LAI (Leaf Area Index) is a key variable in the parametrization of both the effects

LAI is defined as the total leaf surface (single-faced or double-faced) in a column over the ground surface



LAI depends *non-linearly* on seasonality and land use / kind of leaves



LUC	
1	water
2	ice
3	inland lake
4	evergreen needleleaf trees
5	evergreen broadleaf trees
6	deciduous needleleaf trees
7	deciduous broadleaf trees
8	tropical broadleaf trees
9	drought deciduous trees
10	evergreen broadleaf shrubs
11	deciduous shrubs
12	thorn shrubs
13	short grass and forbs
14	long grass
15	crops
16	rice
17	sugar
18	maize
19	cotton
20	irrigated crops
21	urban
22	tundra
23	swamp
24	Desert
25	mixed wood forests
26	Transitional forest

As a first approximation, **LAI** *linearly* depends on **tree height** and **tree density**

$$z_0 = 0{,}06\, h_{tree}\, \rho_{tree}$$

$$LAI = LAI_{min} + (LAI_{max} - LAI_{min}) \frac{z_0 - z_0^{min}}{z_0^{max} - z_0^{min}}$$

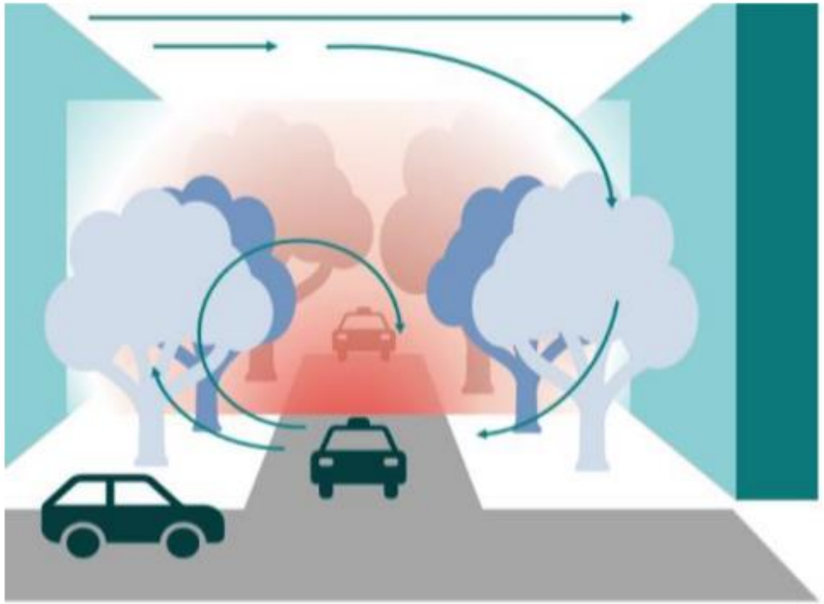
[*] Zhang 2003 – GEM Canada's weather forecast model

Aerodynamic effect

We further distinguish into two situations, depending on the context of each source*

Aerodynamic effect WITHOUT BUILDINGS
The presence of trees (*sparse canopy*) acts as a **drag force**, introducing a **mixing length** that alters the wind profile as a function of **Leaf Area Index**

Aerodynamic effect IN A STREET CANYON
Trees in a street canyon modify the **interaction** between the wind flow and the buildings, squashing the profile at lower levels



[*] We consider just traffic emissions

Aerodynamic effect in a sparse canopy

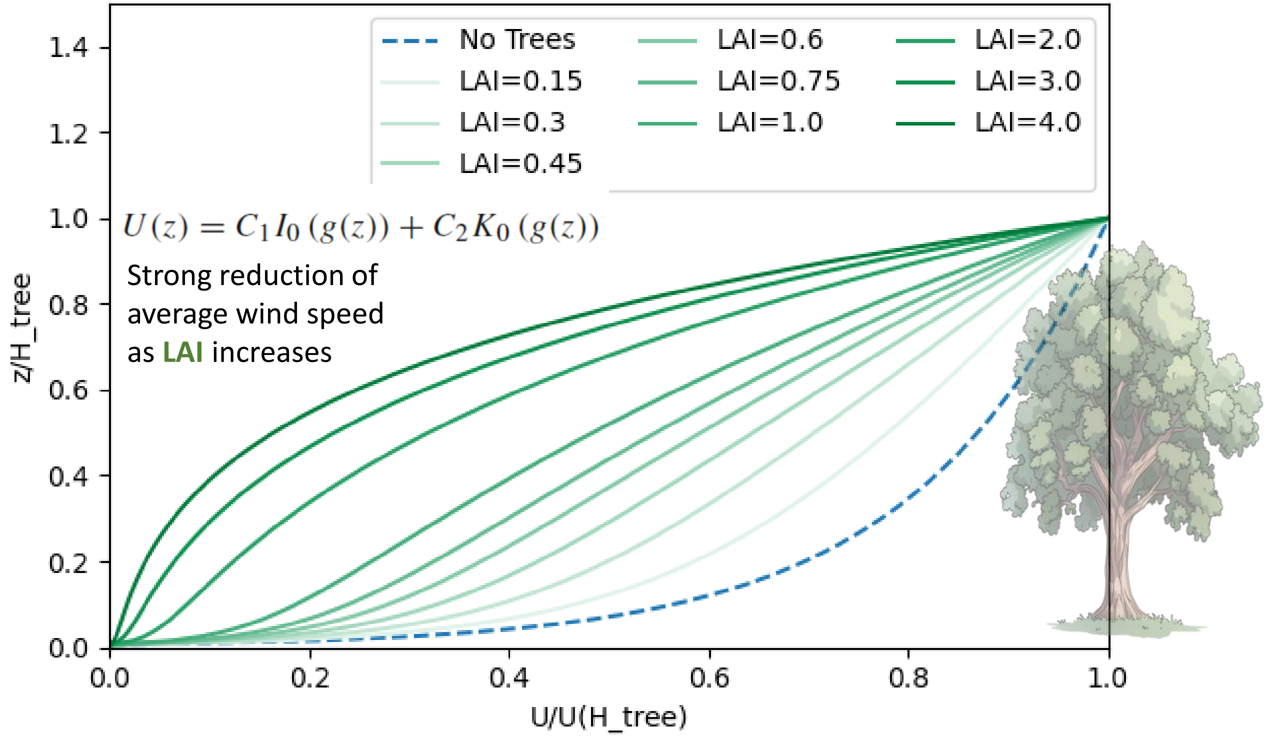
Aerodynamic effect WITHOUT BUILDINGS
The presence of trees (*sparse canopy*) acts as a **drag force** and introduces a **mixing length**, altering the wind profile as a function of **Leaf Area Index**

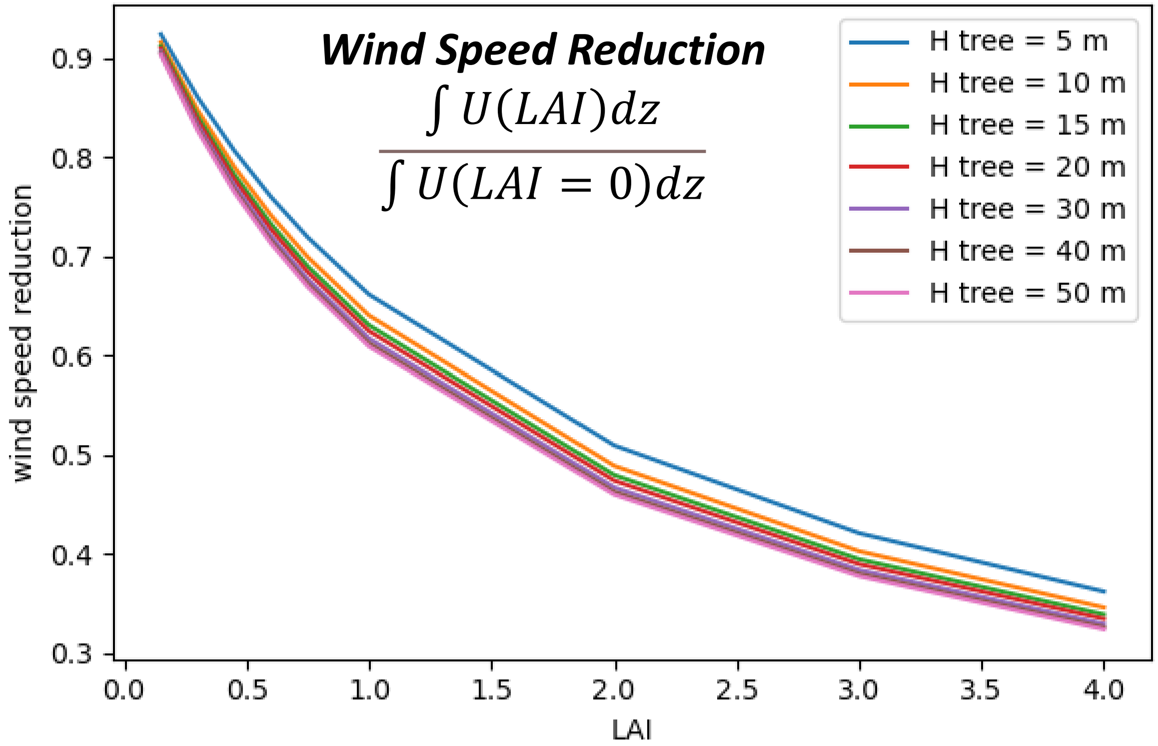
The presence of a canopy is modeled with a drag force in the balance equation

$$-\frac{\partial \tau(z)}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial x} - F_\mathrm{d} \qquad F_\mathrm{d} = C_\mathrm{L} a_0 U(z)\,|U_\mathrm{h}| \qquad \tau(z) = -\langle \overline{u'w'} \rangle = K\frac{\partial U}{\partial z}$$

The eddy diffusivity is parametrized with a LAI dependent mixing length *

$$K = l_\mathrm{m} u_*, \qquad l_\mathrm{m} = \kappa z s, \qquad s(z) = \frac{l_\mathrm{c}}{\left[(l_\mathrm{c})^N + (\kappa z)^N\right]^{1/N}}, \qquad l_\mathrm{c} = 2\beta^3/(C_\mathrm{d} a_0)$$





[*] Wang 2011: The «sparsity» of the canopy is accounted for by introducing a LAI dependent mixing length (not homogeneous along the vertical) in the parametrization of turbulent shear stress tensor. In this way one accounts for both the presence of ground and leaves.

Aerodynamic effect in a street canyon

Aerodynamic effect IN A STREET CANYON

Trees in a street canyon modify the **interaction** between the wind flow and the buildings, squashing the profile at lower levels

Without trees

Wind profile *Depends on* →

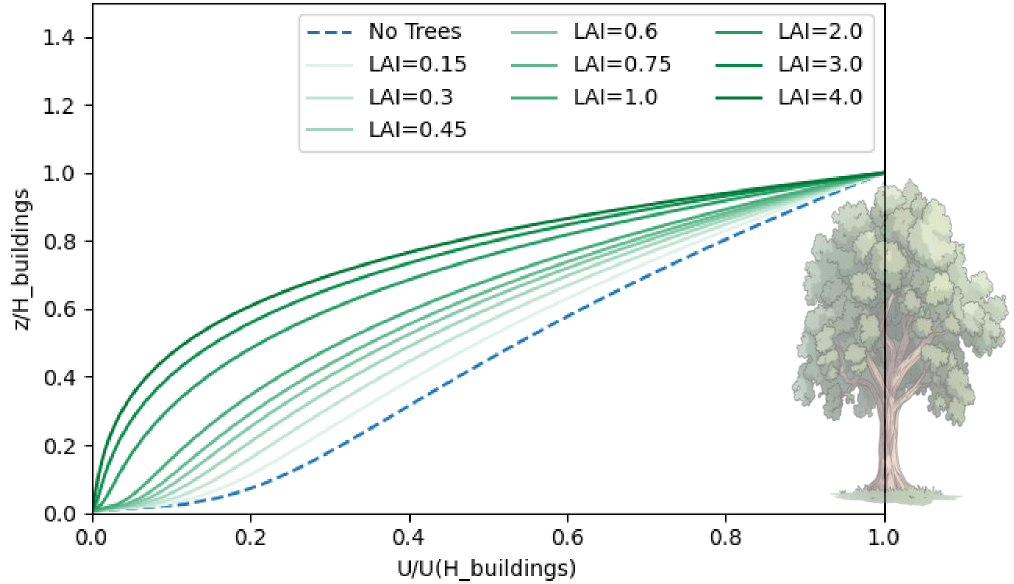
- **Canyon deepness (height/width)**
- **Street – wind angle**

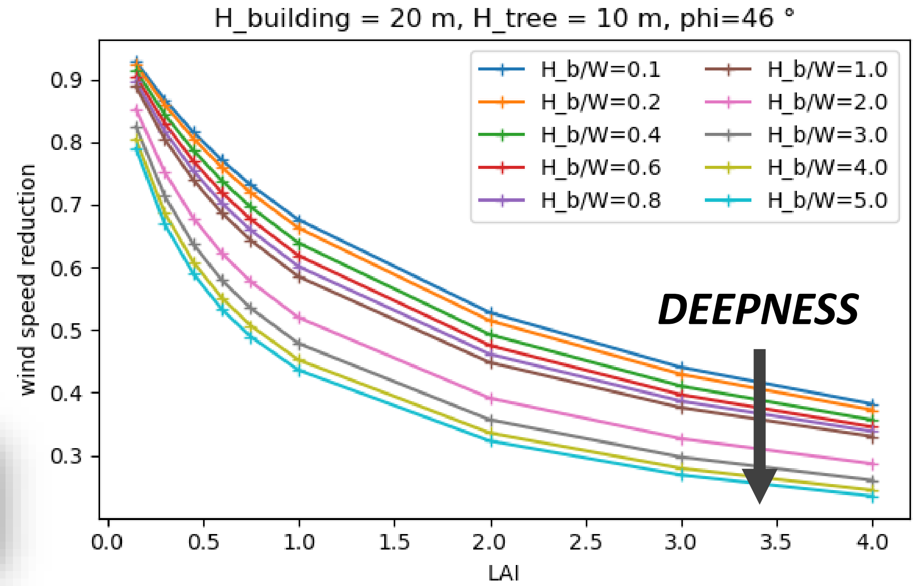
With trees

Wind profile *Depends on* →

- **Canyon deepness (height/width)**
- **Street – wind angle**
- **Leaf Area Index**
- **Tree height**

$$s_H = \begin{cases} \dfrac{l_{c_b}}{l_{c_b} + \kappa H} & \text{without tree} \\[2ex] \dfrac{l_{c_b}\, l_{c_t}\, f_{b\times t}}{\kappa\, H\,(l_{c_b} + l_{c_t}\, f_{b\times t}) + l_{c_b}\, l_{c_t}\, f_{b\times t}} & \text{with trees.} \end{cases}$$





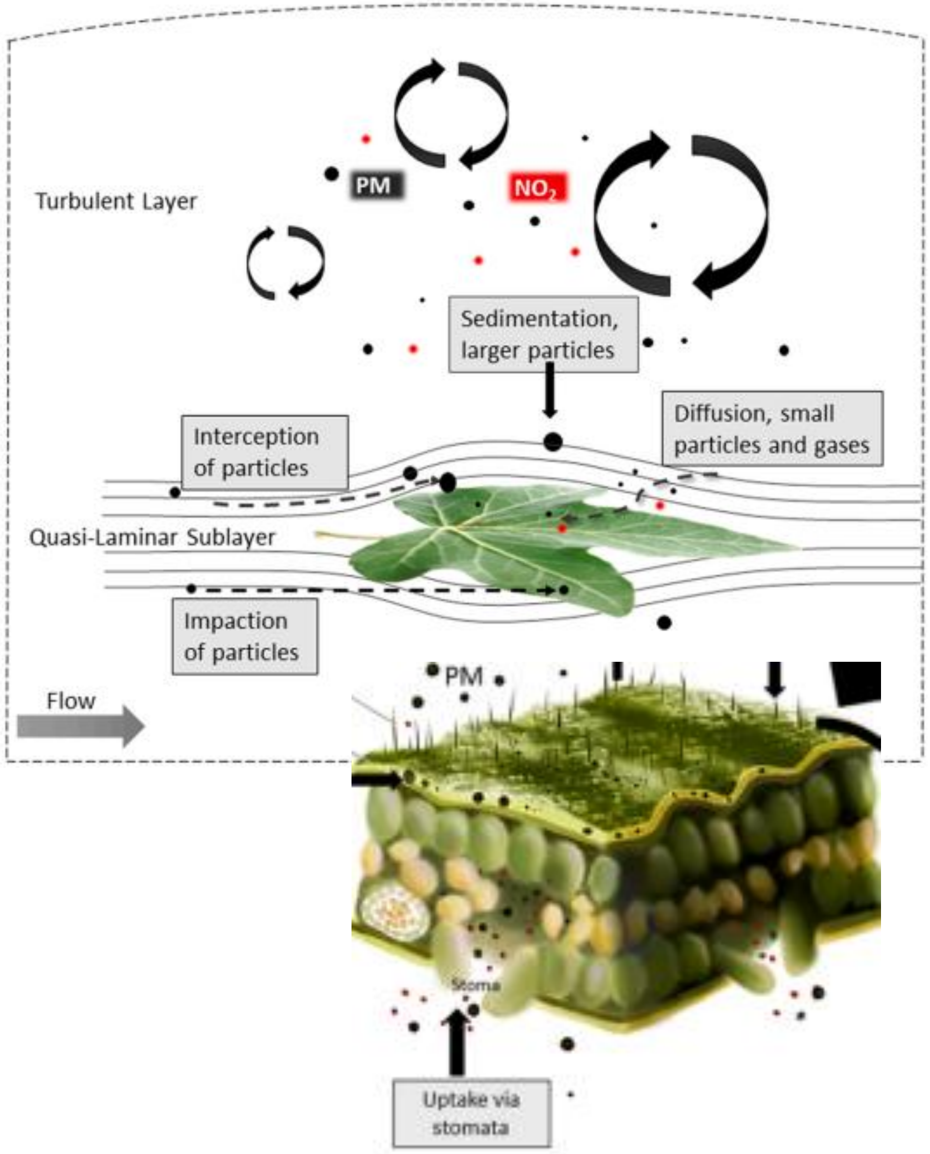
[*] Maison et al 2022 – Wang 2011: Wind profile in a canyon is computed adapting the Wang profile in sparse canopies. The interaction between trees and buildings is accounted by modifying the buildings mixing length. Free coefficients of the new parametrization are fixed comparing the profiles with CFD simulations (Saturne)

Dry deposition on leaves

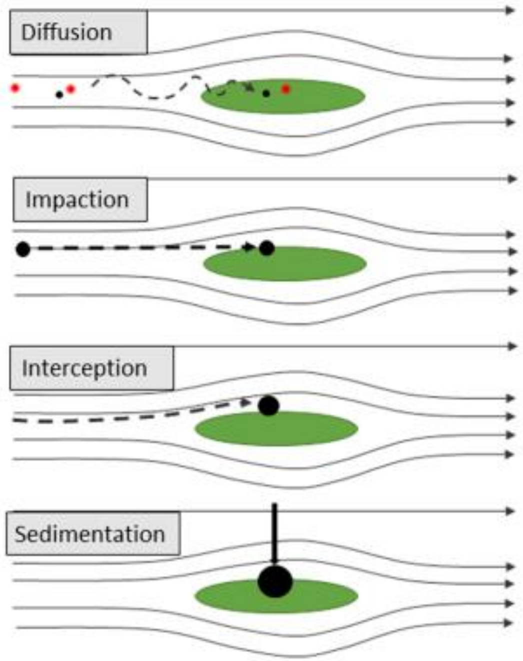
Dry deposition is the mechanism through which pollution mass leaves the atmospheres and attaches to surfaces

The parameter controlling the efficiency of the process is the **deposition velocity**, which depends on

- *Kind of surface (leaf)*
- *Leaf Area Index*
- *Seasonality / Diurnal cycle*
- ***Kind of pollutant***
- ***Windspeed***
- ***Atmospheric stability***



Dry Deposition mechanisms



$$\frac{d^2\gamma^+}{dz^{+2}} + \alpha \frac{d\gamma^+}{dz^+} - Q\gamma^+ = 0 \quad \text{with} \quad Q = \frac{h.\mathrm{LAI}.V_T}{K_p}.$$

$$\alpha = \left(\frac{k_x \mathrm{LAI}}{12\kappa^2 (1-d/h)^2}\right)^{1/3} \phi_m^{2/3} \left(\frac{h-d}{Lo}\right),$$

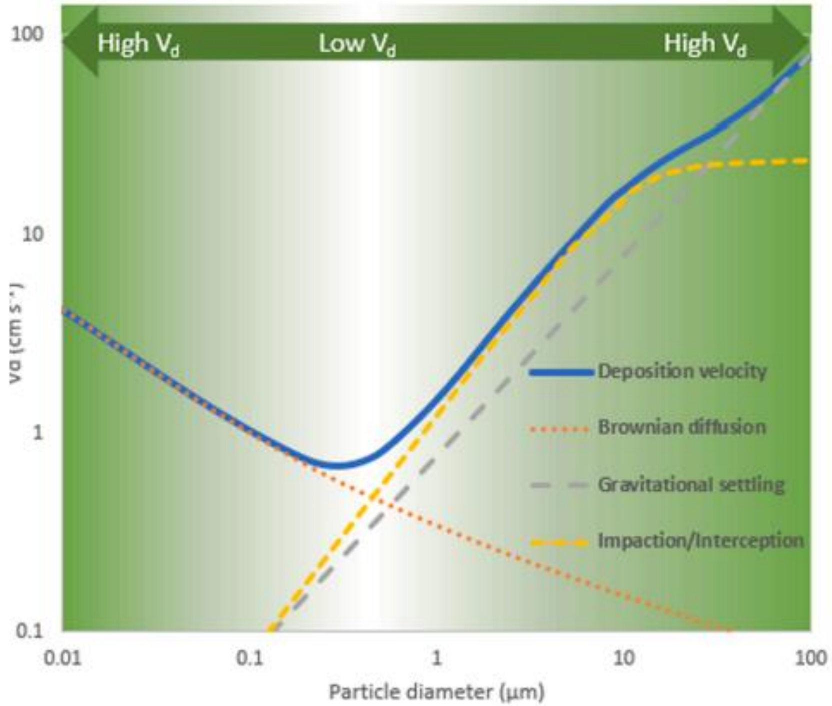
$$V_T(z) = E_T(z) u_f(z) \quad \text{with}$$
$$E_T = \frac{U_h}{u_*}(E_B + E_{IN} + E_{IM}) + E_{IT},$$

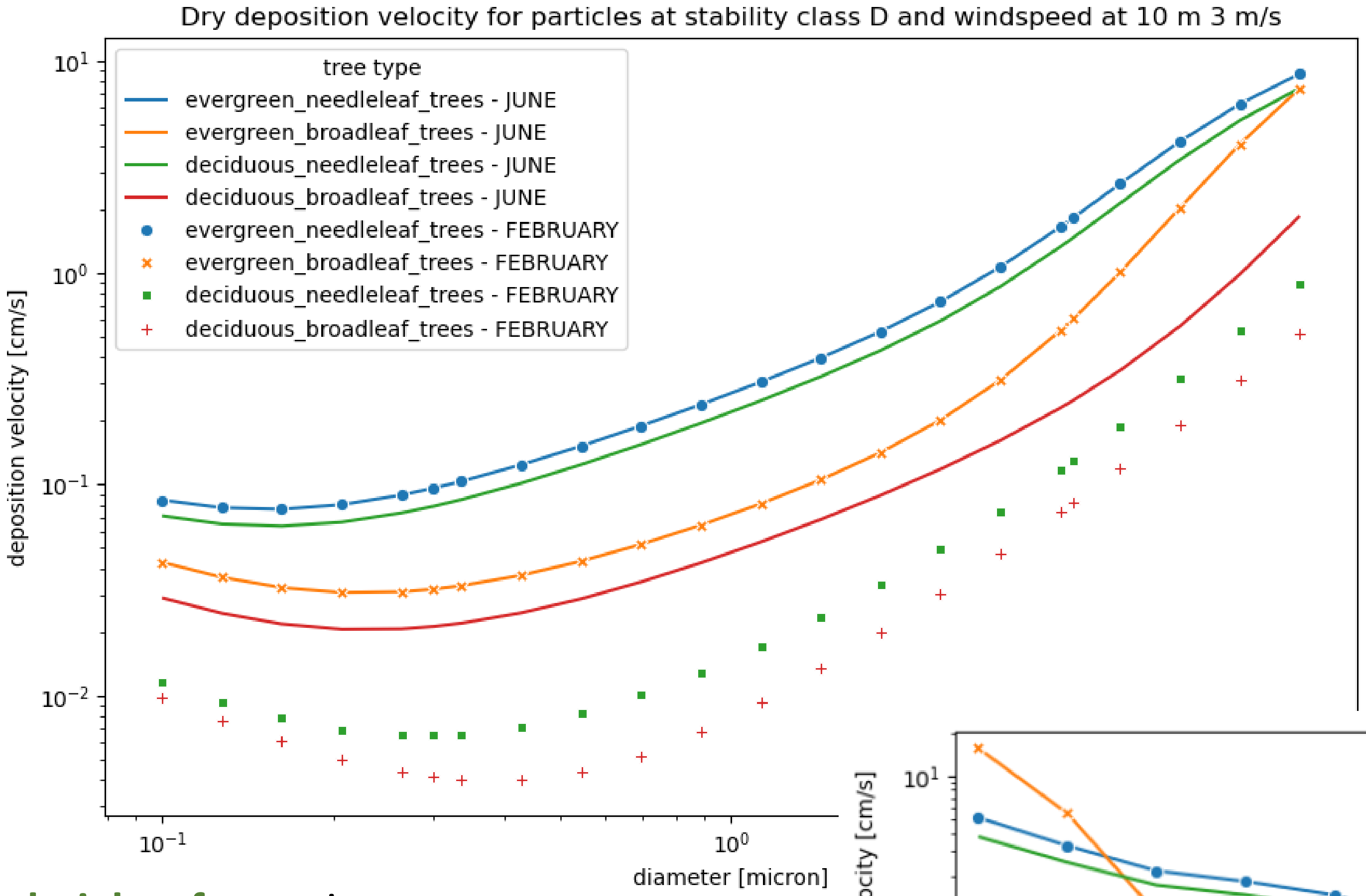
[*] Linden et al 2023 – Petroff et al 2010 – Zhang 2001/2003

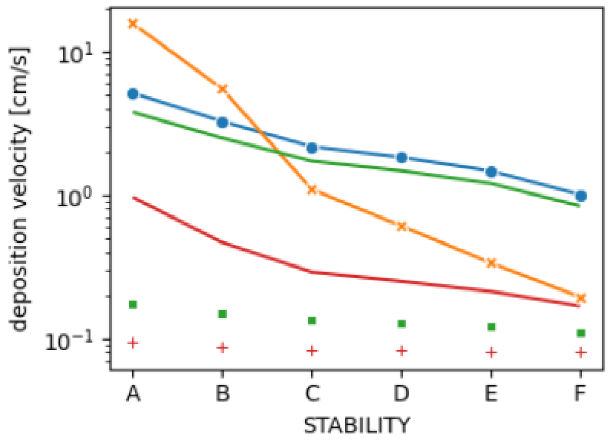
[*] Petroff et al 2010 – Zhang 2001/2003: Introduction of an efficiency parameter of collection on leaves over turbulent mixing in the balance equation for concentration. LAI becomes an explicit parameter of the deposition velocity

Dry deposition on leaves

For **particulate matter**, deposition velocity strongly depends on the **diameter** of particles.







The kind of leaves, the density of trees and the height of trees impact on

- **Surface roughness**
- **Effective size of leaf element exposed**
- **Flow reduction within the canopy**

affecting every sub-process of the deposition

Parametrizing dry deposition for urban planning and assessment

Applying phenomenological parameterizations of dry deposition on leaves in an urban environment to develop a synthetic model for fast and effective urban planning.

A classification of the effects of dry deposition on concentration reduction is obtained performing **PMSS** simulations in a range of deposition velocities for specific traffic sources (road segments), in classified meteorological input conditions

For each combination of the following varables a PMSS simulation is performed (normalized emission)

Variable	N. of classes	Classes
Wind direction [degrees from North]	**8**	0° - 45° - 90° - 135° - 180° 225° - 270° - 315 °
Windspeed [m/s]	**6**	1 – 2 – 3 – 5 – 7 – 9
Atmospheric stability [Pasquill]	**5**	A – B – C – D – E/F
Deposition velocity [cm/s]	**10**	0.1 – 0.4 – 0.7 – 1 – 1.5 – 2 – 3 – 4 – 5 – 6
Buildings context	**4**	Cluster representant optimized with K-means

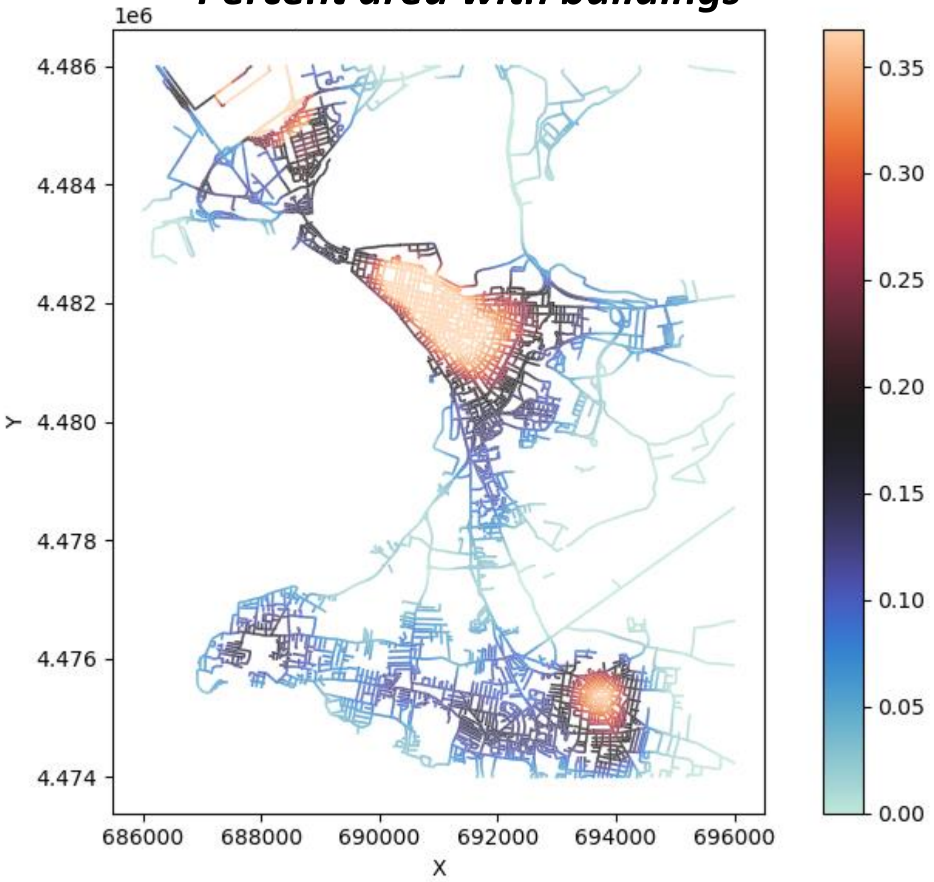
*A total of **9600** ground concentration fields produced,*
*to be used to **parametrize** the concentration reduction as effect of dry deposition*

Classification of emissive sources for dry deposition

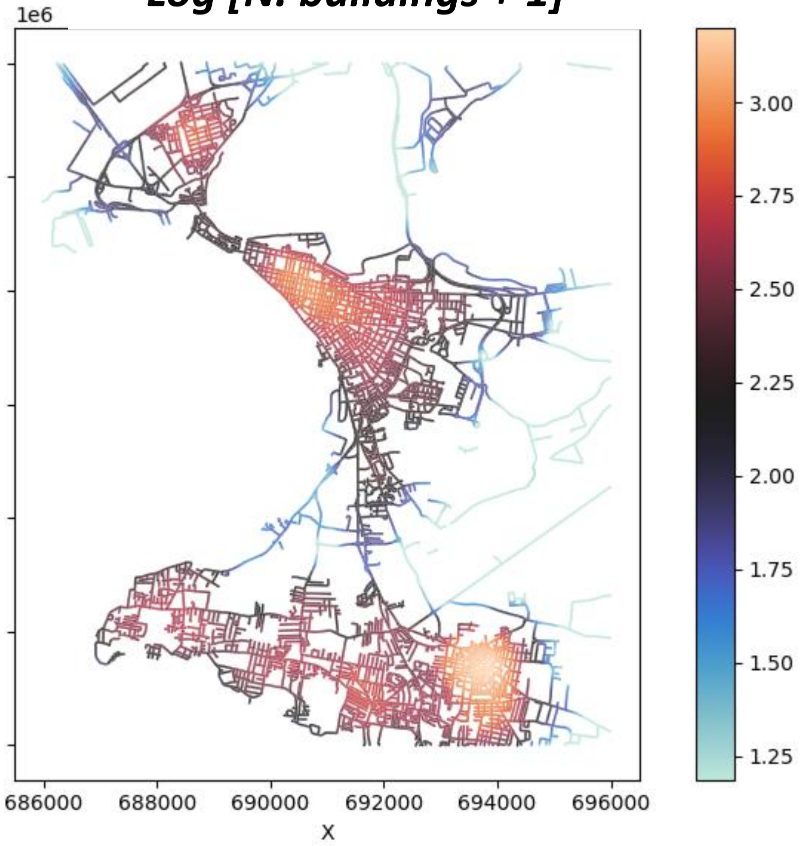
We perform a **classification** of sources (road segments) based on the ***urban context*** in which they are embedded.

The following attributes are considered in a 500 m buffer around the source

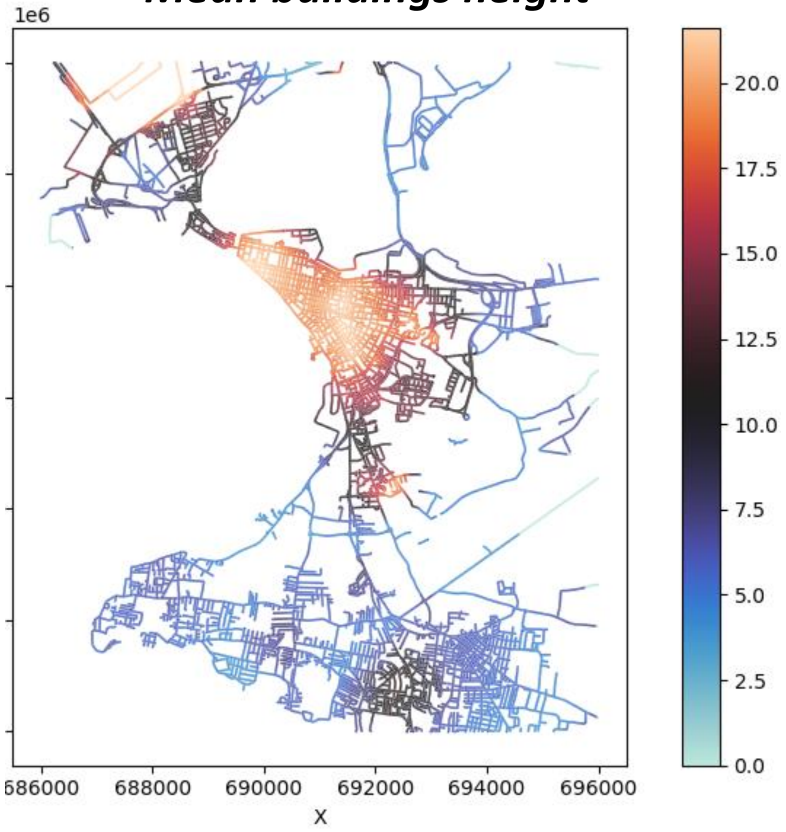
Percent area with buildings



Log [N. buildings + 1]



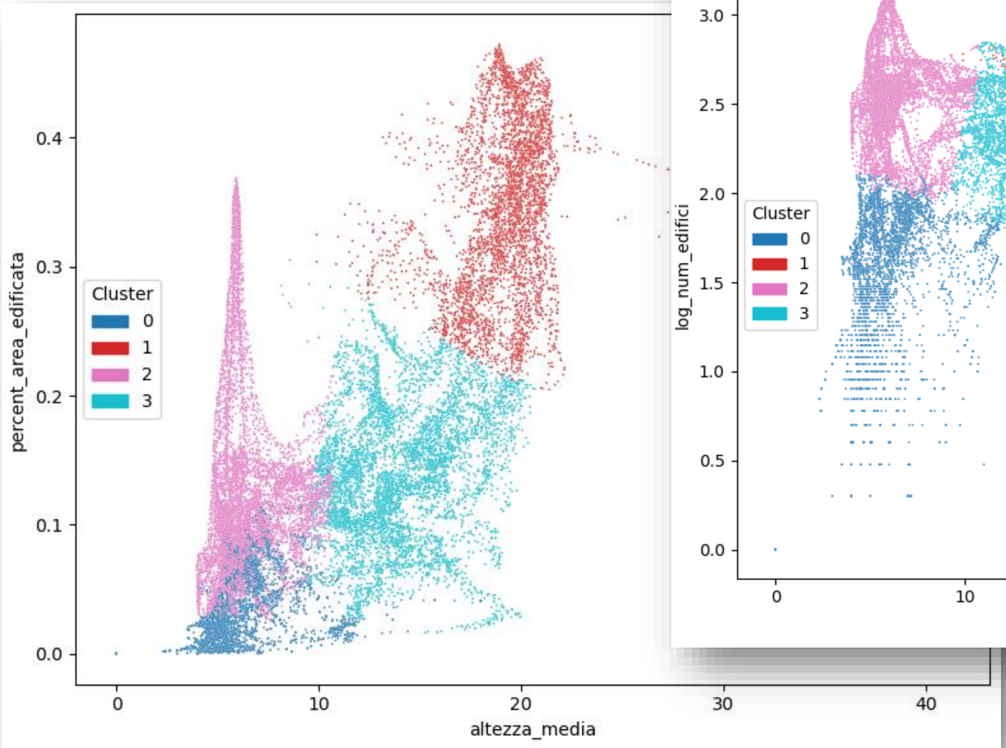
Mean buildings height

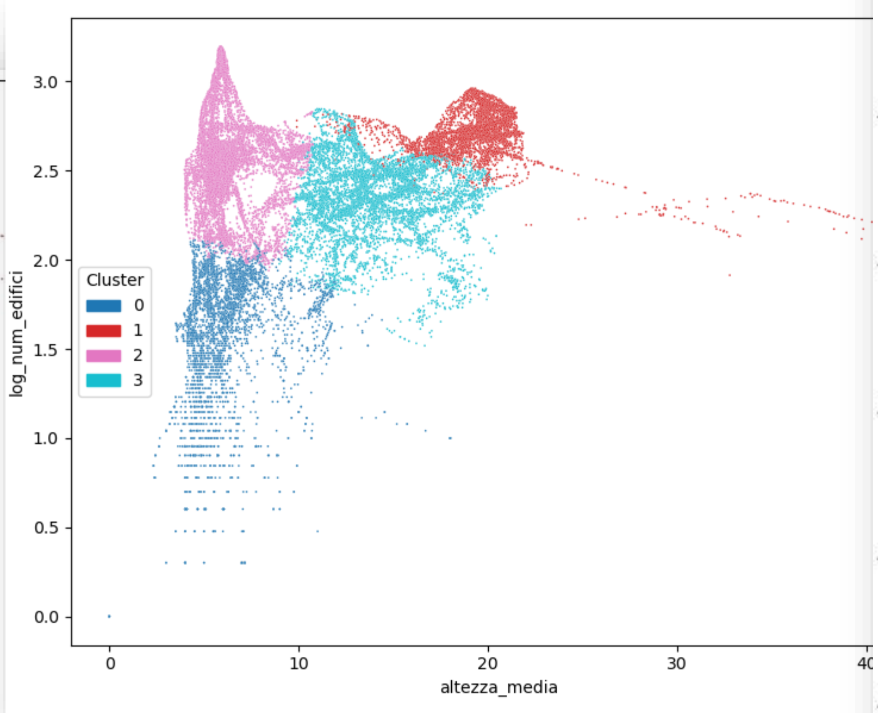


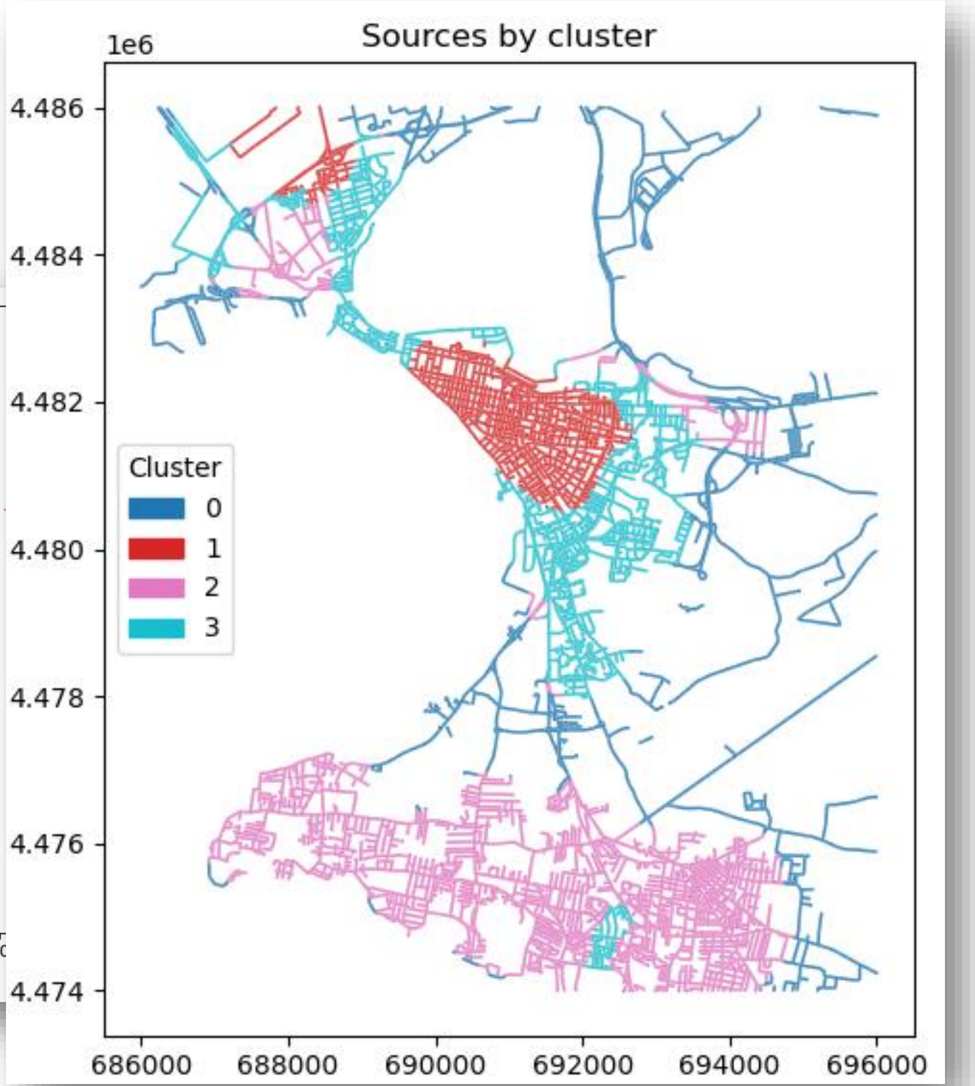
Classification of emissive sources for dry deposition

A data-driven **clustering** is performed by using an unsupervised **Machine Learning** algorithm ***K-Means***

Cluster 0: sparsely distributed short buildings
Cluster 1: many high and dense buildings
Cluster 2: many short buildings
Cluster 3: average distributed buildings





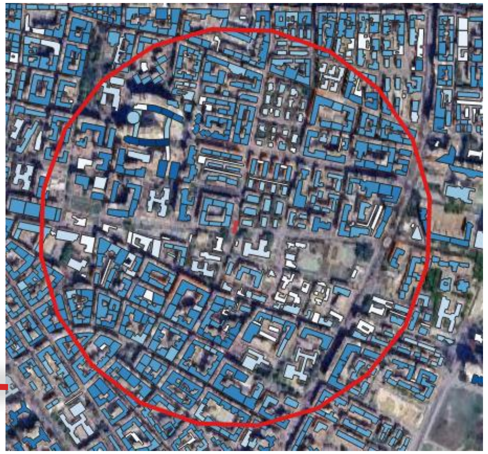


Classification of emissive sources for dry deposition

Cluster 0: sparsely distributed short buildings
Cluster 1: many high and dense buildings
Cluster 2: many short buildings
Cluster 3: average distributed buildings

Cluster 3

Cluster 1



Cluster 2

Cluster 0

Four representative sources for each of the urban context cluster

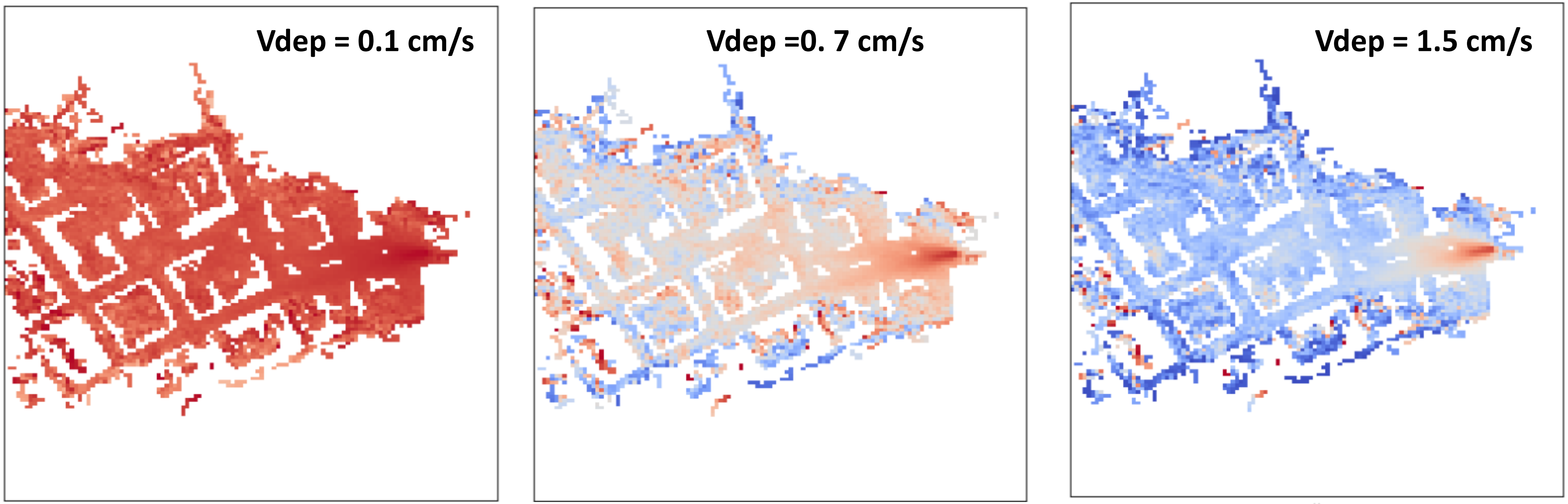
These are the sources used to simulate the effect of deposition on different urban context

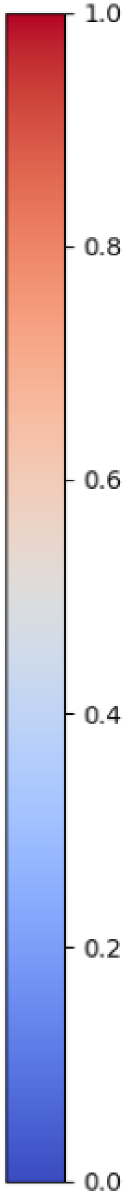
Dry deposition within an urban environment: PMSS simulations

For every *combination* of wind **direction**, wind **speed**, **stability**, **deposition velocity** and **urban cluster** a field of **concentration reduction** is computed

$$R(x,y) = \frac{C\left(x, y, v_{\text{dep}}\right)}{C\left(x, y, v_{\text{dep}} = 0\right)}$$

Concentration ratio

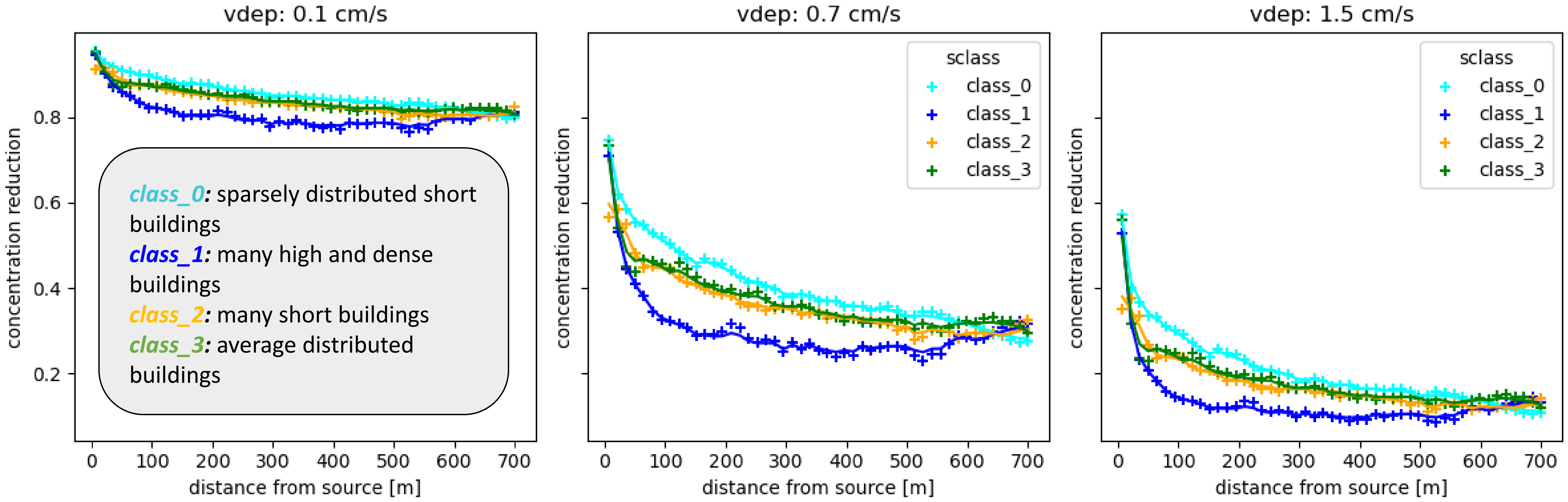




CLUSTER 1 - DIR 90° - SPEED 1 m/s – STABILITY E

Dry deposition within an urban environment: dependence on distance

Concentration reduction (as a function of distance)



SPEED 1 m/s – STABILITY E – LAI = 1 (*variable LAI not implemented in PMSS*)

For each combination, we parametrize a **reduction law as a function of distance**. The interpolated parameters will be used by the **convolutor** to compute the reduction on the fly

$$R(d) = \frac{e^{-\alpha d}}{(1+\beta d)^{\gamma}} f(LAI) \qquad f(LAI) \approx exp\left[(1-LAI)\frac{v_d}{U}\frac{d}{h}\right]$$

Natural based solutions integrated in the Digital Twin (CoKer)

The user selects the areas where to apply natural based solutions as **geo-referenced disjoint polygons** (eg on *QGIS*)

Each polygon must intersect at least one street segment and having the following attributes:

- **Type of leave** (broad/needle – evergreen/deciduous)
- **Trees density** (average surface percentage occupied by trees)
- **Trees height**

ID	H_TREE	TREE_TYPE	TREE_DENS
1	10	evergreen_needleleaf	0,5
2	15	deciduous_needleleaf	0,8
3	20	evergreen_broadleaf	0,9
…	…	…	…

Natural based solutions must be provided to the Digital Twin in **shapefile format**

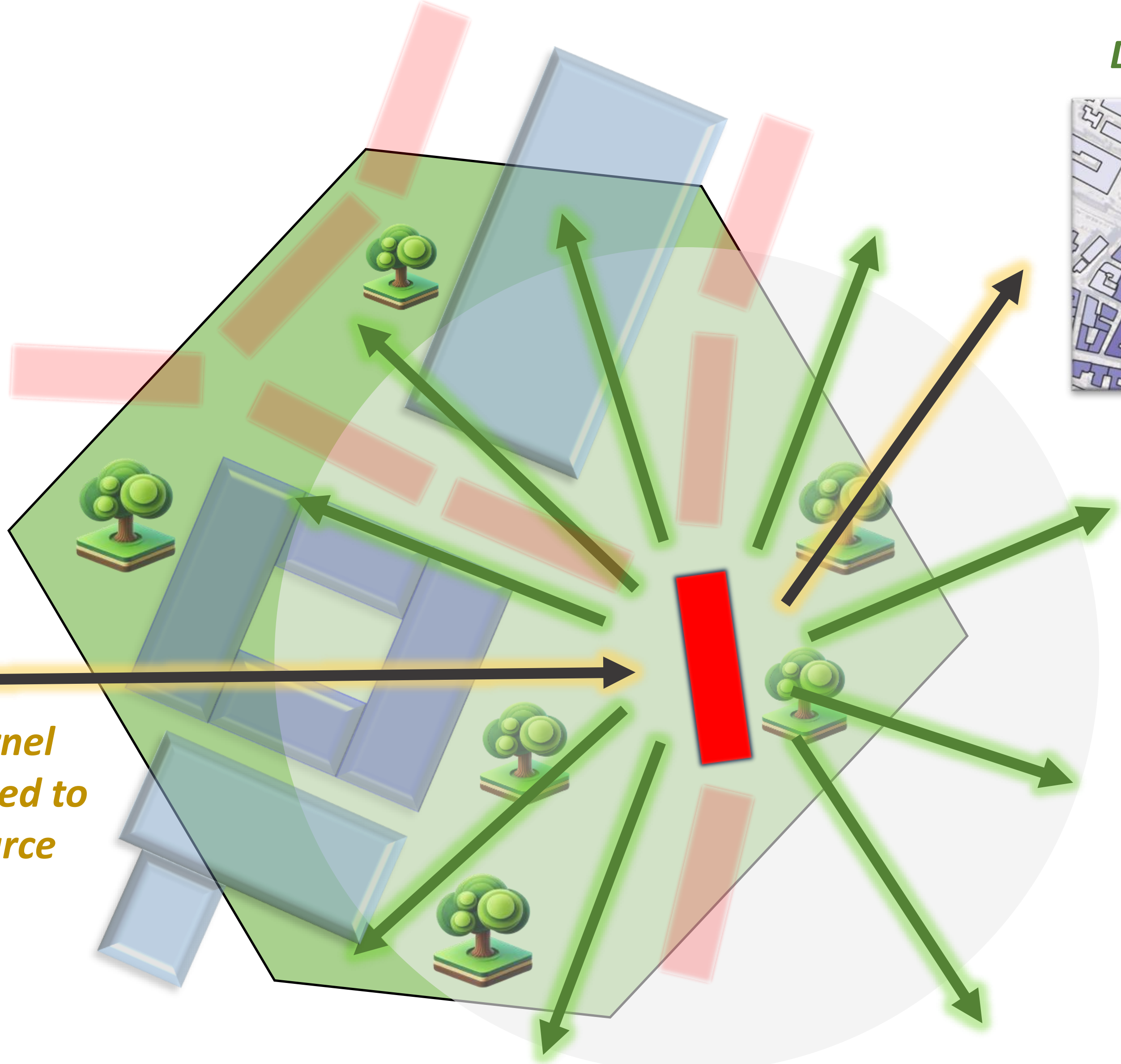
Natural based solutions integrated in the Digital Twin (CoKer)

AERODYNAMIC EFFECT

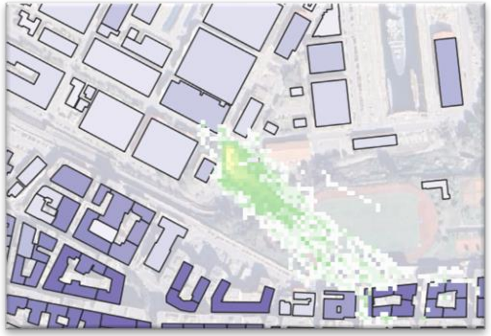
Original Windspeed
7 m/s

Reduced windspeed
3 m/s

Kernel applied to source

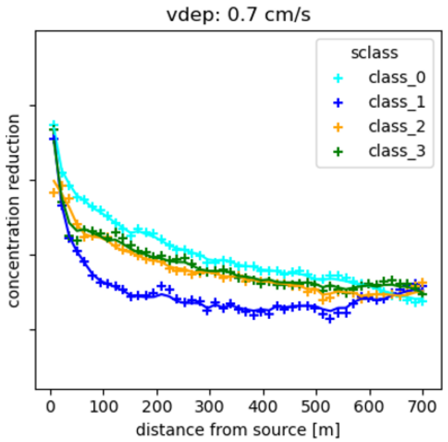


DEPOSITION EFFECT



Deposition has a radial effect from source.

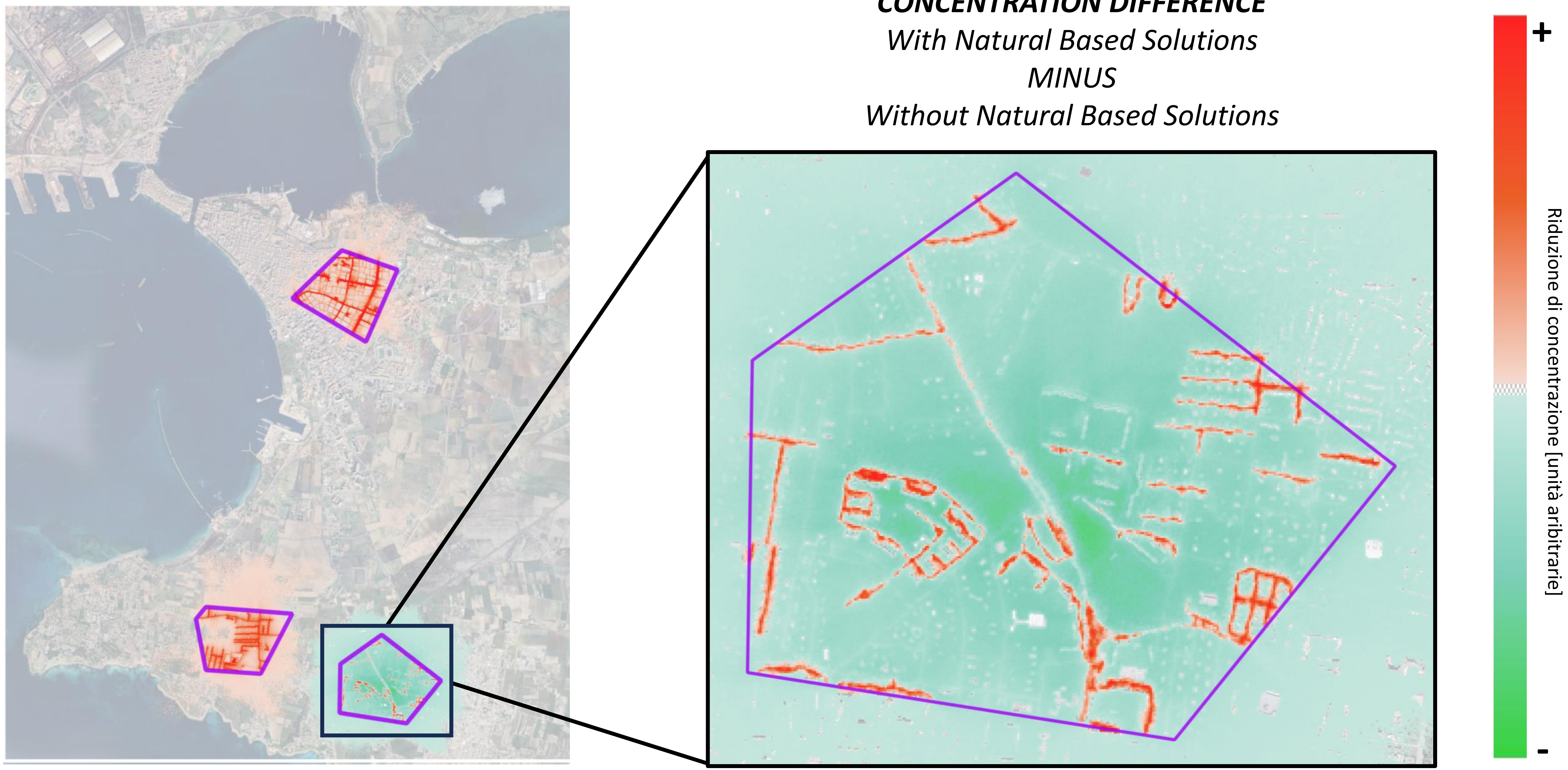
It extends all over the kernel, beyond the region with natural based solutions*



*Outside the polygon boundary, the deposition is constant and keeping the value on the boundary.

Natural based solutions integrated in the Digital Twin (CoKer)

CONCENTRATION DIFFERENCE
With Natural Based Solutions
MINUS
Without Natural Based Solutions



Aerodynamic effect mainly peaked along the roads, Deposition enhanced with distance. Typically, aerodynamic effect is dominant

THANK YOU

ARIANET