23rd International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes

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Integrating Nature-Based-Solutions into citywide air quality reconstruction at microscale

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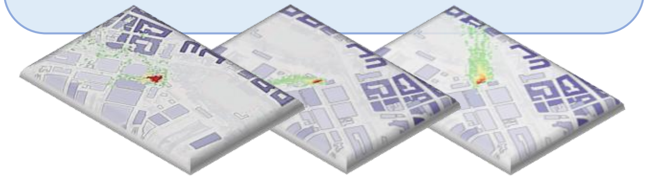
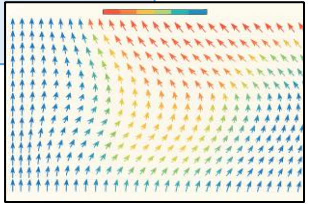
Microscale modelling framework for emission and NBS scenarios

- Based on convolution of agnostic-model dispersion kernels
- Citywide and at microscale, with explicit modelling of buildings
- Allows for fast emission scenario simulations (eg vehicular traffic)
- Allows for evaluation of NBS interventions

Site-dependent dispersion kernels database
with normalized emissions



Driver Meteo
Hourly field / timeseries of ground wind & stability at regional scale



Emissions
Spatialised over a street graph

Convolutor
- *Kernel picking* on the basis of **meteo** and **emissions** hour by hour;
- *Convolution* and *time average*

Nature-Based Solutions (NBS)
Shapefile with trees features

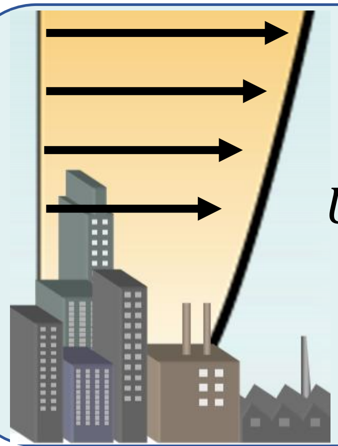
Annual mean concentration

Taranto domain
Lx = 9 km - Ly = 14 km
Dxy = 5 m

Normalized dispersion kernels construction – meteo downscaling

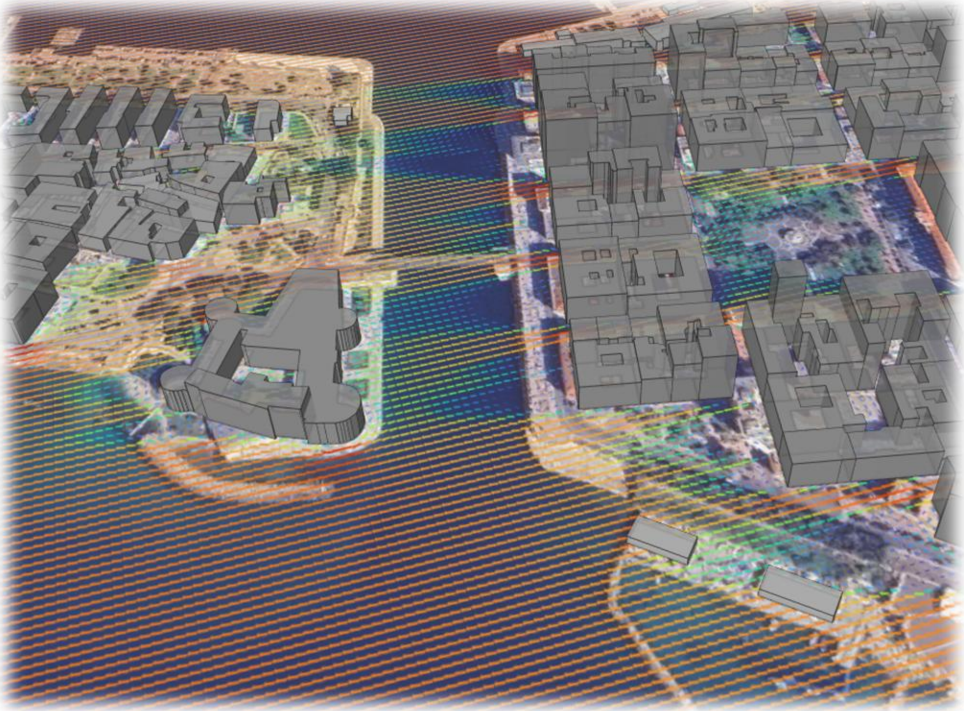
Inlet wind profiles
6 wind speeds at 10m
8 wind directions at 10m
5 stability classes
240 combinations

3D Meteo downscaling
PSWIFT
Adapt the wind profiles to buildings
240 simulations



$$U = U_{10}\left(\frac{z}{10}\right)^{\alpha}$$

Buildings
Vectorial Shapefile



Wind profiles are built raising the wind at 10 m using **power laws** which depend on **stability** and imposing **urban surface roughness**

PMSS DRIVEN KERNELS

Normalized dispersion kernels construction – dispersion

Inlet wind profiles
6 wind speeds at 10m
8 wind directions at 10m
5 stability classes
240 combinations

3D Meteo downscaling
PSWIFT
Adapt the wind profiles to buildings
240 simulations

3D Dispersion simulations
PSPRAY
Stationary dispersion from traffic emission at microscale
240 simulations

PMSS
DRIVEN
KERNELS

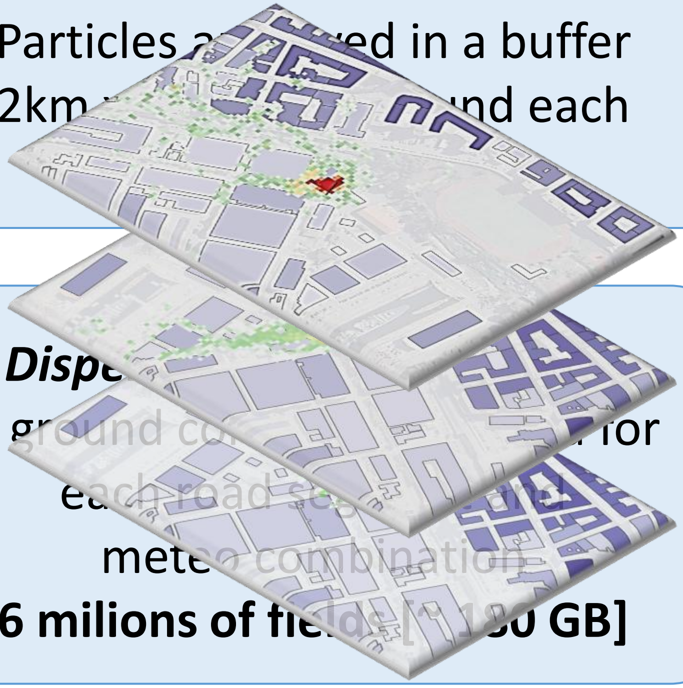
Buildings
Vectorial Shapefile

Street Graph
4000 polylines

Discretized graph
26000 road segments with normalized emissions

Particles a... ed in a buffer 2km ... und each

Dispe...
A ground co... for each road se... meteo combination
6 milions of fie... [~ ... GB]

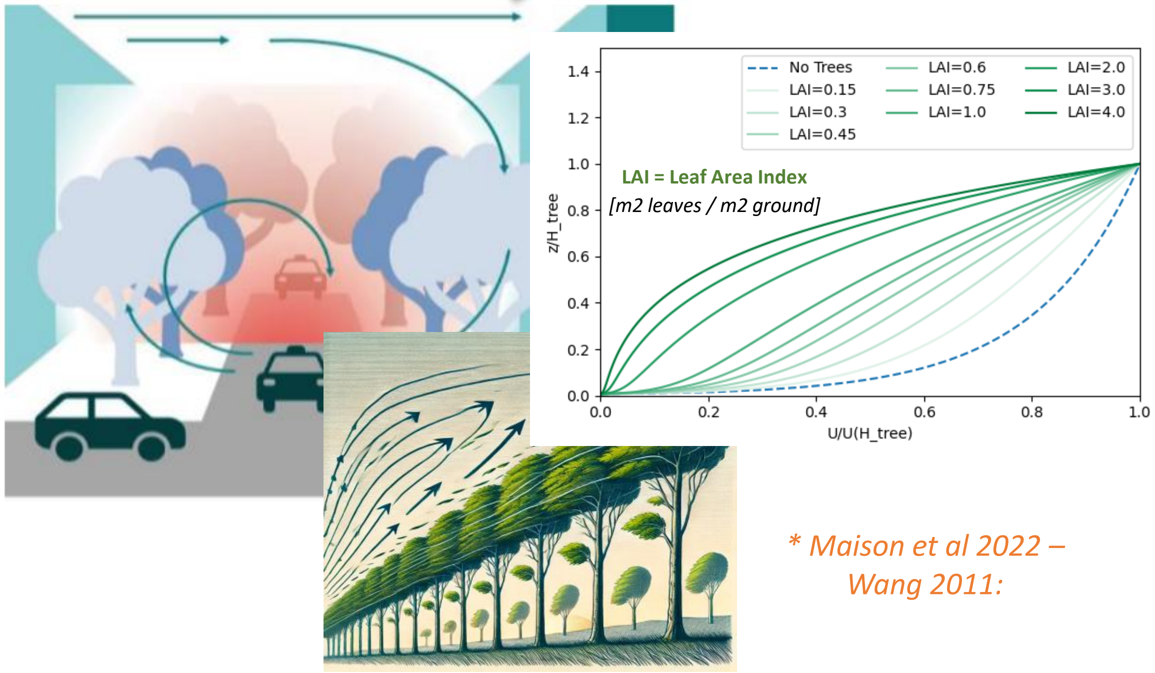


Nature Based Solutions Modelling

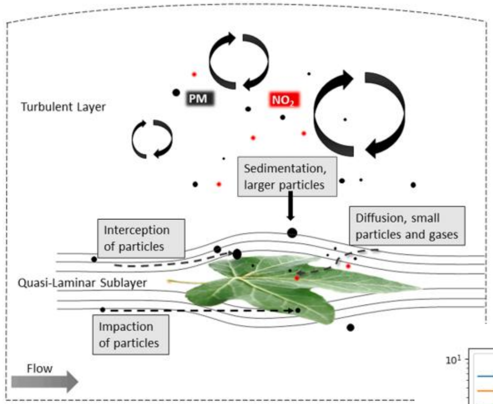
We model two antagonist effects of nature based solutions on concentration in an urban context

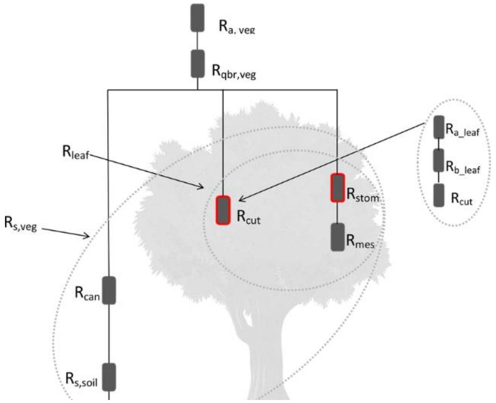
Aerodynamic effect
The presence of trees modifies the wind profile, reducing on average the wind speed
The net effect is an **increase of the concentration**

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

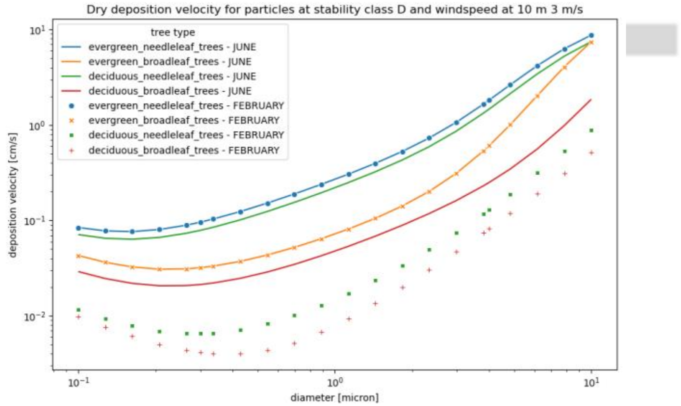


** Maison et al 2022 – Wang 2011:*





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



Aerodynamic effect in a sparse canopy

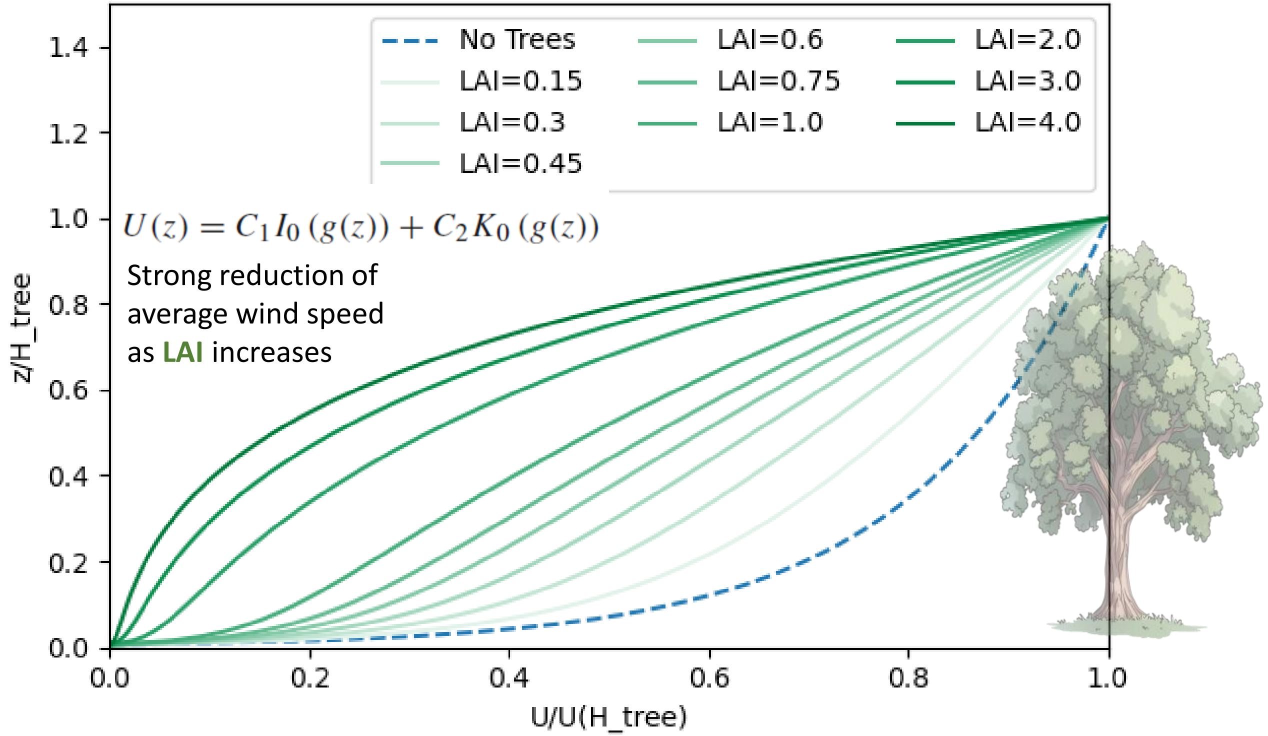
Aerodynamic effect WITHOUT BUILDINGS
The presence of trees (*sparse canopy*) acts as a **drag force** and introduces a **mixing length**, altering the wind profile as a function of **Leaf Area Index**

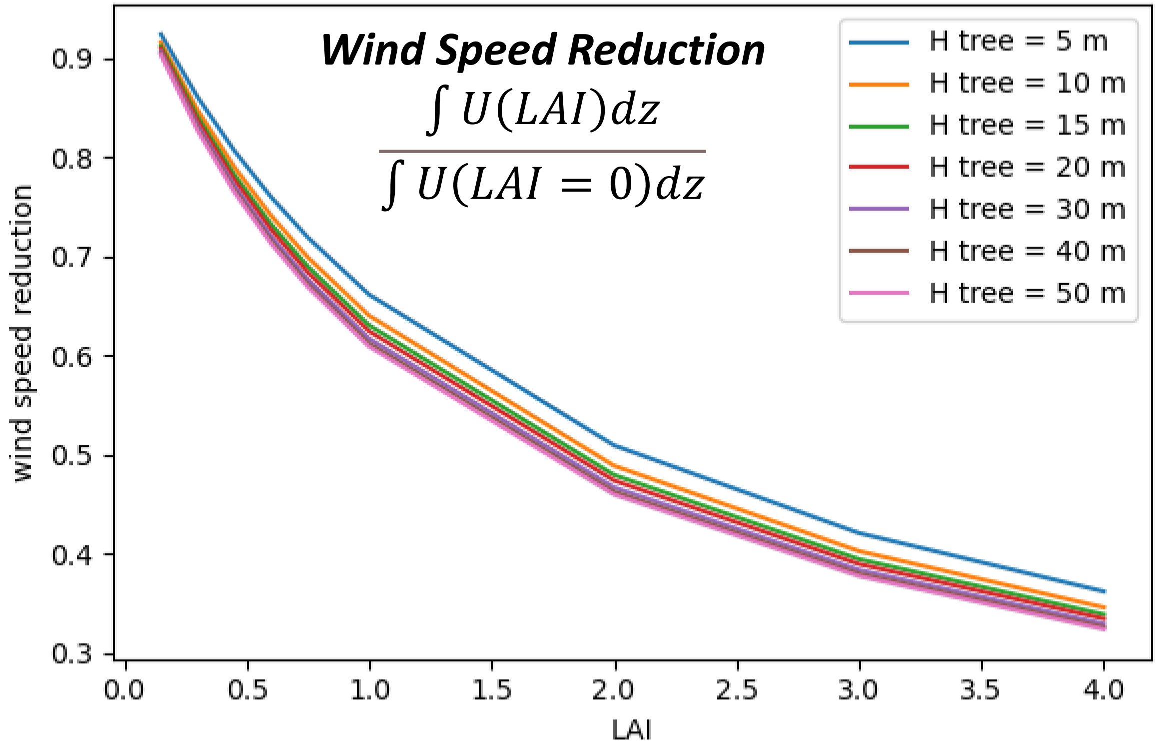
The presence of a canopy is modeled with a drag force in the balance equation

$$-\frac{\partial \tau(z)}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial x} - F_d \qquad F_d = C_L a_0 U(z)\,|U_h| \qquad \tau(z) = -\left\langle \overline{u'w'} \right\rangle = K\frac{\partial U}{\partial z},$$

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

$$K = l_m u_*, \qquad l_m = \kappa z s, \qquad s(z) = \frac{l_c}{\left[(l_c)^N + (\kappa z)^N\right]^{1/N}}, \qquad l_c = 2\beta^3/(C_d a_0)$$





[*] 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

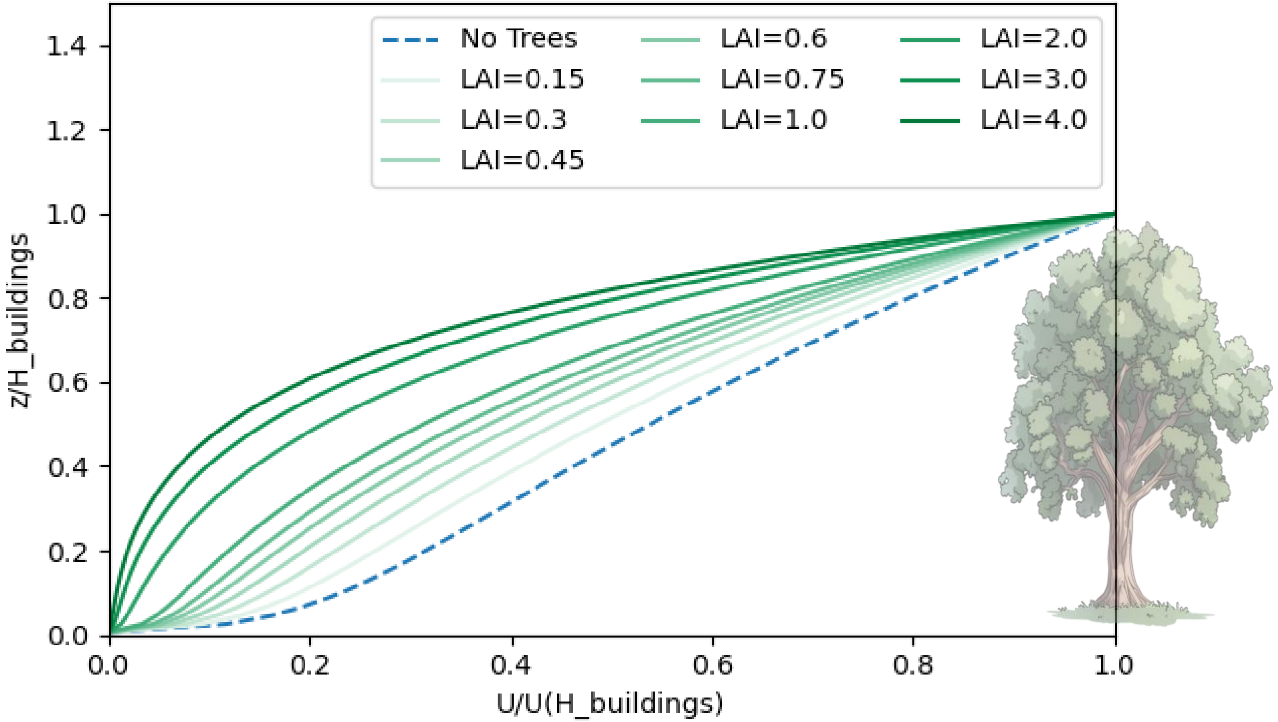
Trees in a street canyon modify the **interaction** between the wind flow and the buildings, squashing the profile at lower levels

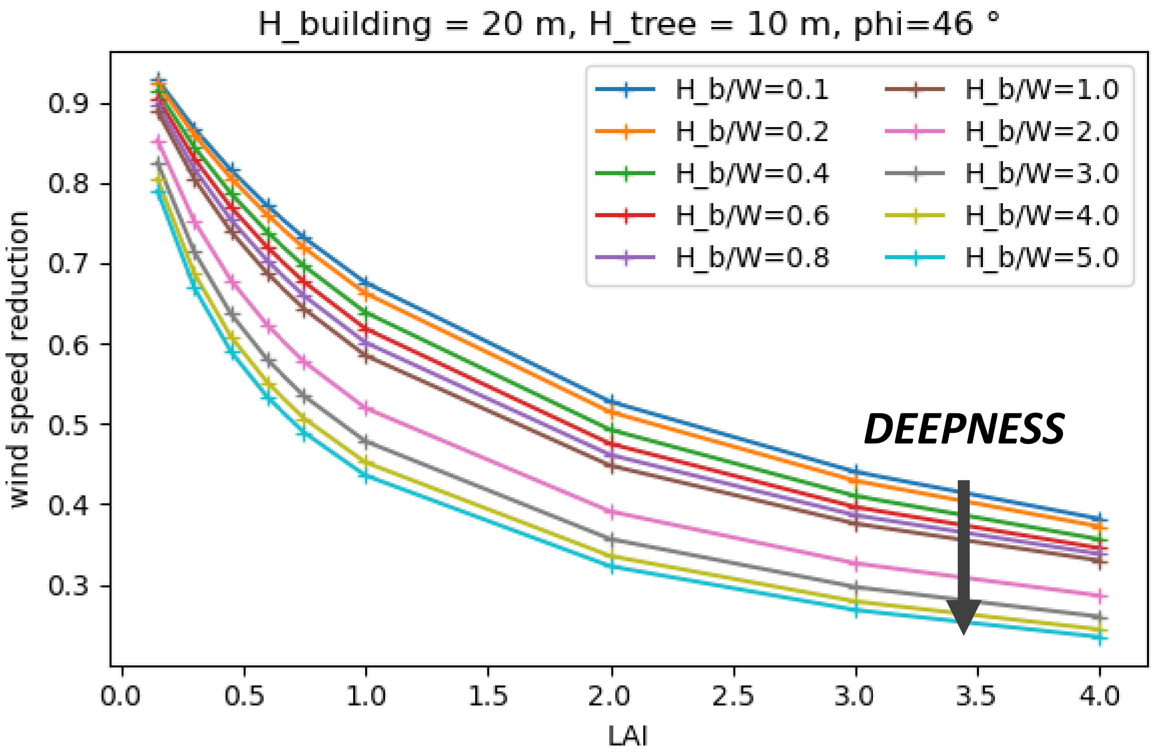
Wind profile *Depends on* →

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

Mixing length modification

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





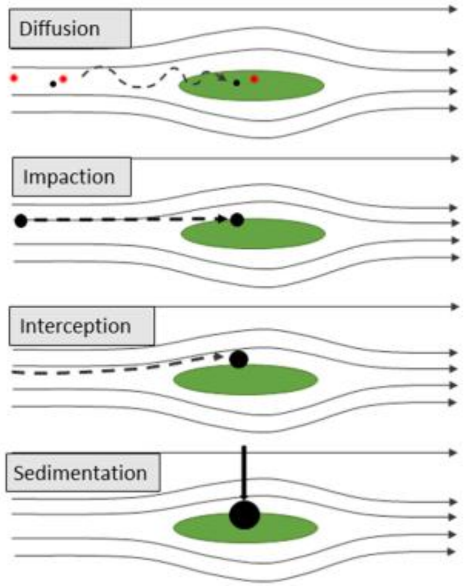
[*] Maison et al 2022 – Wang 2011: Wind profile in a canyon is computed adapting the Wang profile in sparse canopies. The interaction between trees and buildings is accounted by modifying the buildings mixing length. Free coefficients of the new parametrization are fixed comparing the profiles with CFD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

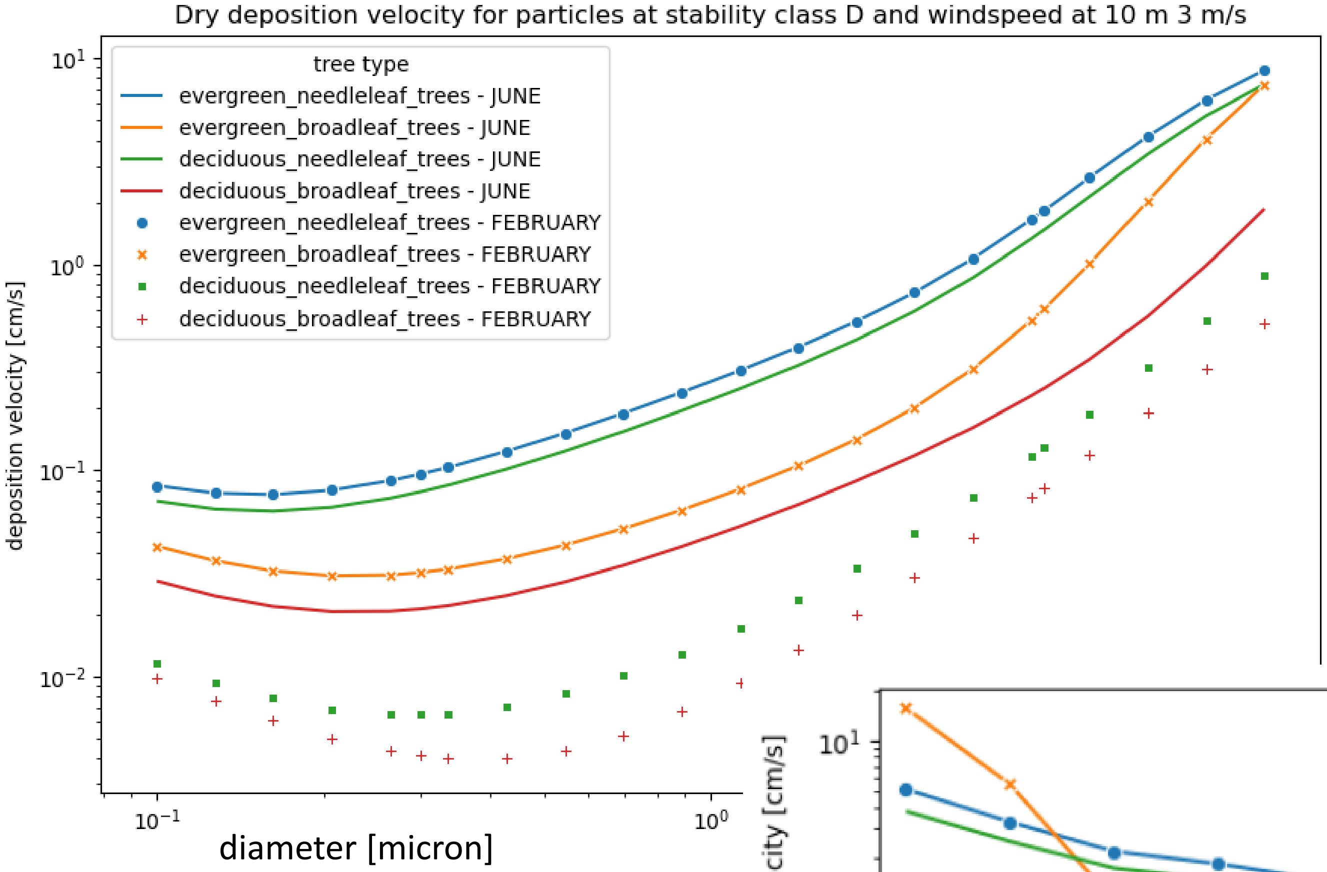
Dry deposition on leaves

Deposition velocity is the efficiency parameter, which depends on

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

Variables like **kind of leaves**, the **tree cover** and the **height of trees** impact on these parameters, affecting every sub-process of the deposition



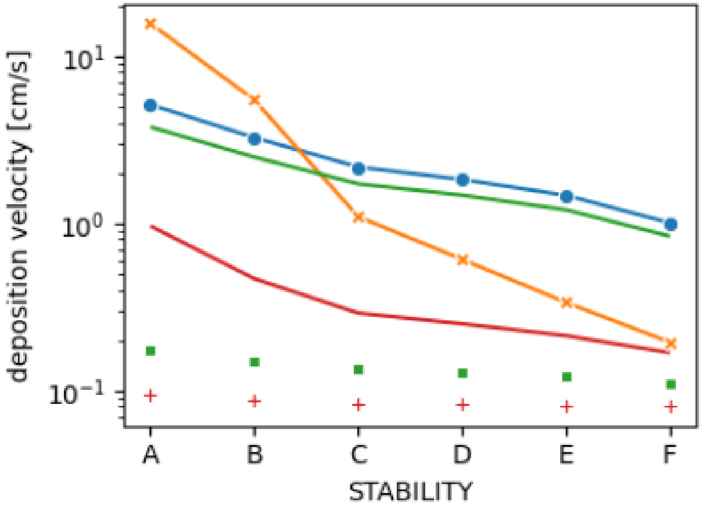


$$\frac{d^2\gamma^+}{dz^{+2}} + \alpha\frac{d\gamma^+}{dz^+} - Q\gamma^+ = 0 \quad \text{with} \quad Q = \frac{h.\mathrm{LAI}.V_T}{K_p}.$$

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

$$V_T(z) = E_T(z)u_f(z) \quad \text{with}$$

$$E_T = \frac{U_h}{u_*}(E_B + E_{IN} + E_{IM}) + E_{IT},$$



[*] 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

Parametrizing dry deposition for urban planning and assessment

Application of leaf dry deposition parameterizations in urban environment
developing a synthetic yet effective model,
suitable for integration within the kernel convolution framework

A **classification** of the effects of dry deposition on concentration reduction is derived from **PMSS** dispersion simulations, performed across **a range of deposition velocities** and **classified meteorological conditions**, for a **set of emission sources** representative of different urban contexts

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

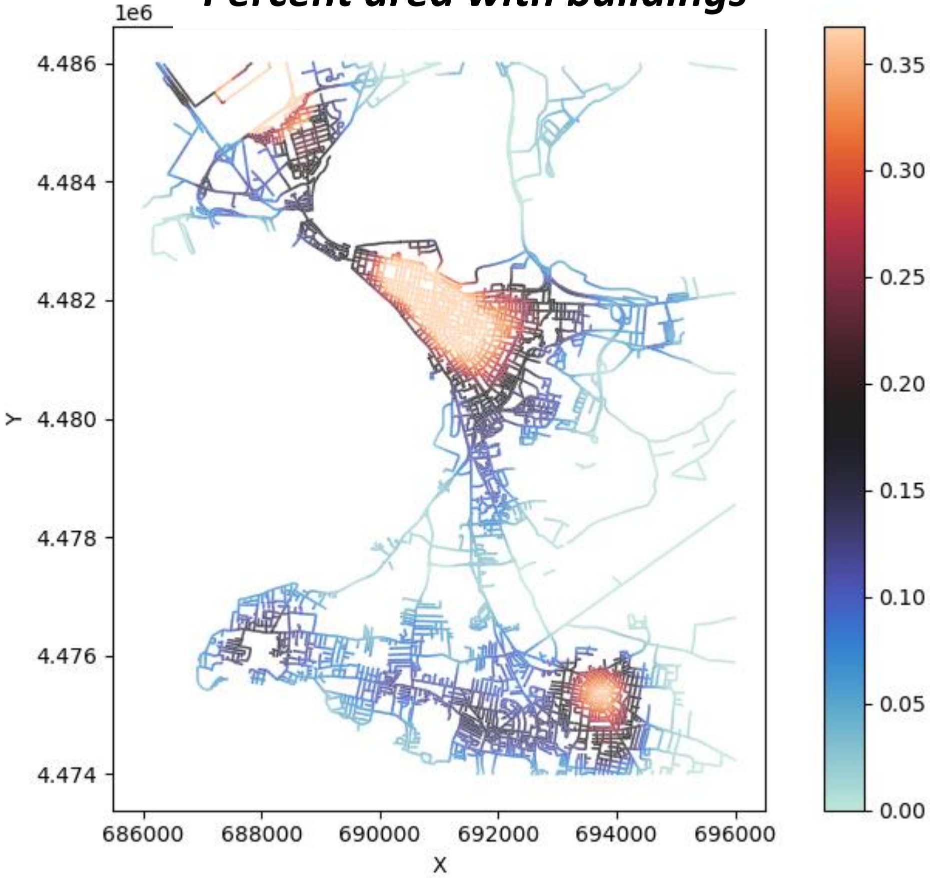
*A total of **9600** ground concentration fields produced,*
*to be used to **parametrize** the concentration reduction as effect of dry deposition*

Classification of emissive sources for dry deposition

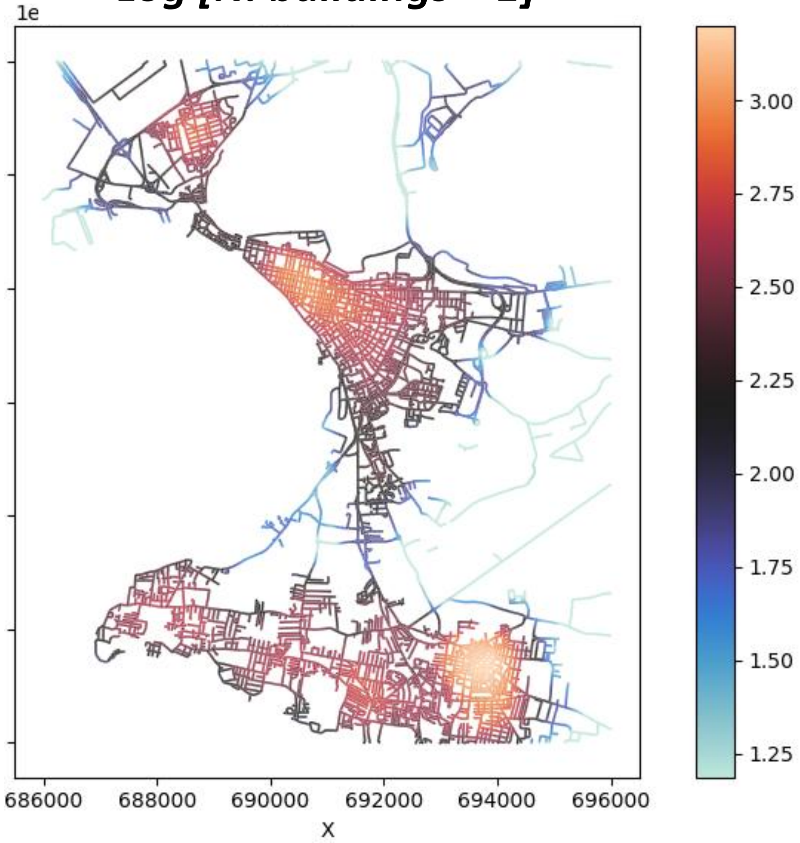
We perform a **classification** of sources (road segments) based on the ***urban context*** in which they are immersed.

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

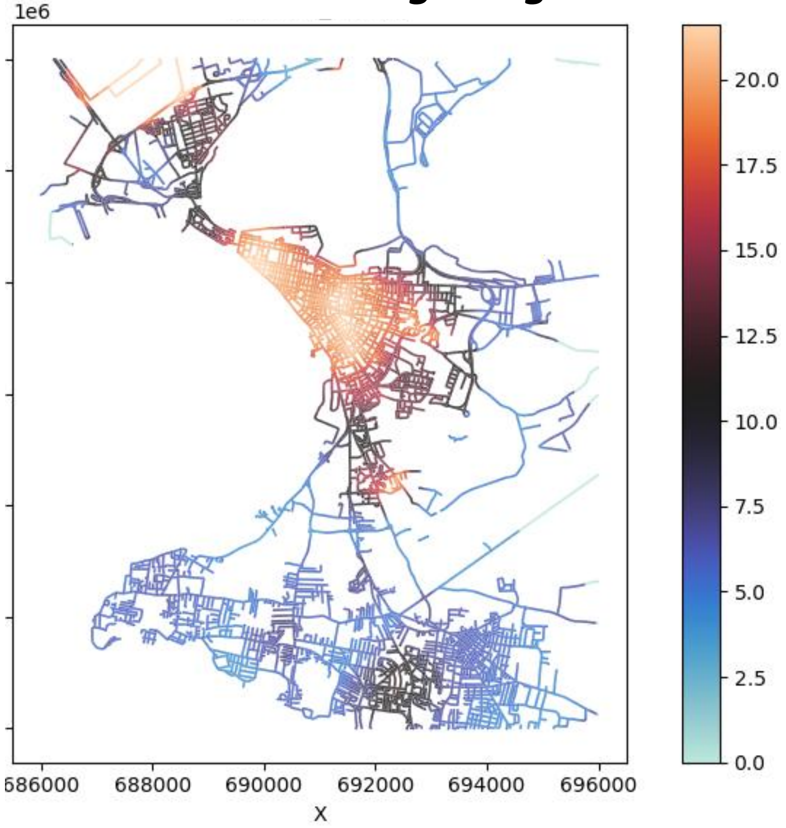
Percent area with buildings



Log [N. buildings + 1]



Mean buildings height



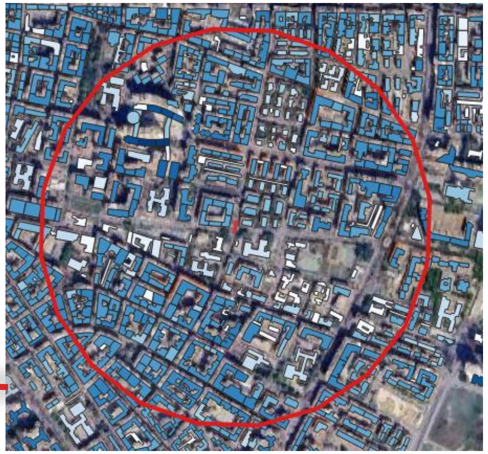
Classification of emissive sources for dry deposition

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

Cluster 3

Cluster 1



Cluster 2

Cluster 0

Four representative sources, one for each of the urban context cluster

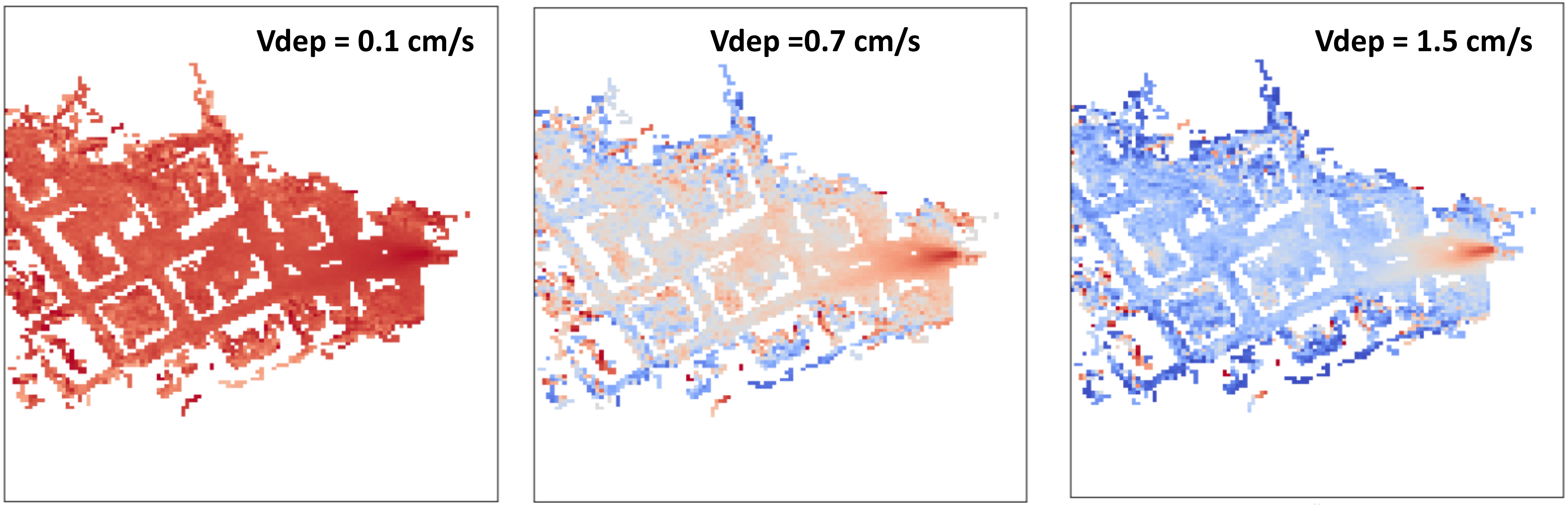
These are the sources used to simulate the effect of deposition on different urban context

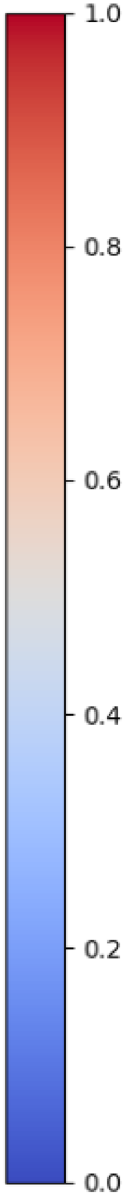
Dry deposition within an urban environment: PMSS simulations

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

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

Concentration ratio

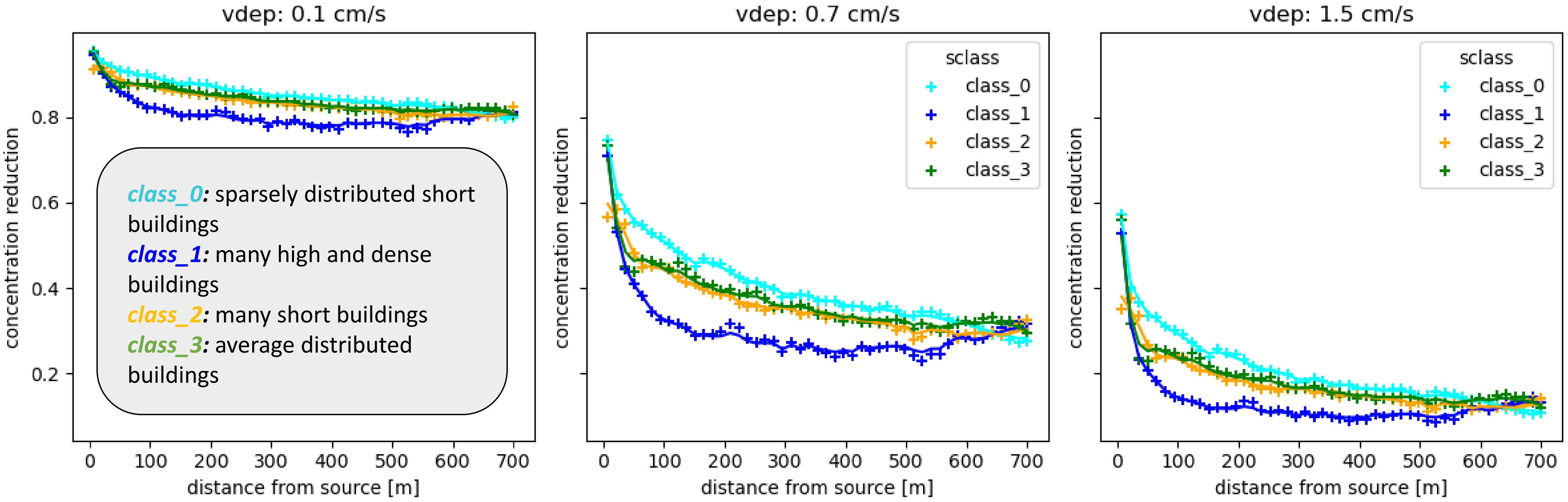




CLUSTER 1 - DIR 90° - SPEED 1 m/s – STABILITY E

Dry deposition within an urban environment: dependence on distance

Concentration reduction (as a function of distance)



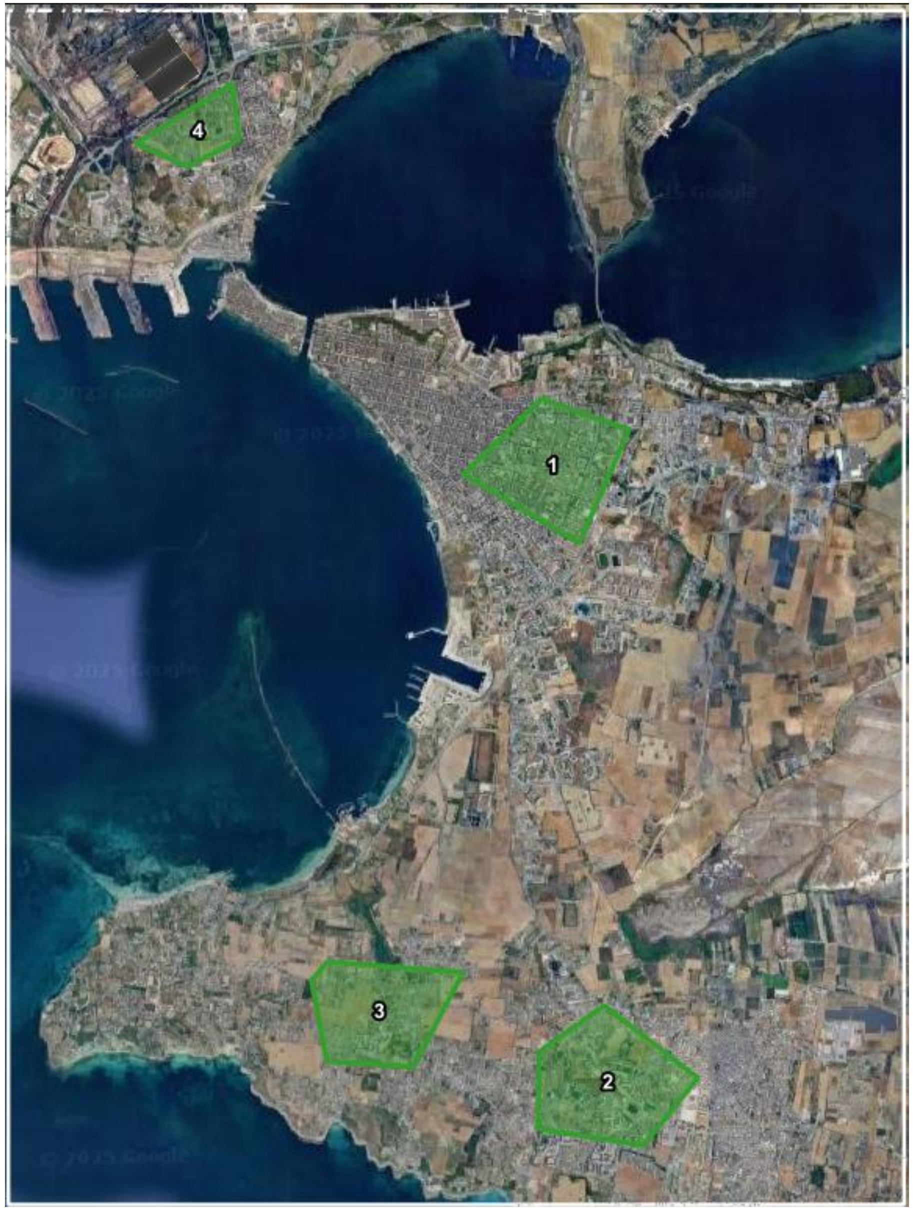
SPEED 1 m/s – STABILITY E – LAI = 1 (*variable LAI not implemented in PMSS*)

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

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

*The extra exponential factor accounts for deposition on a total surface which is larger than ground area for LAI > 1

Nature based solutions integrated in the modelling framework



The input are areas where to apply NBS as **geo-referenced disjoint polygons**

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

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

ID	Height [m]	Leaf type	Coverage [%]
1	10	evergreen_needleleaf	50
2	10	deciduous_broadleaf	50
3	10	evergreen_needleleaf	50
4	10	deciduous_needleleaf	80

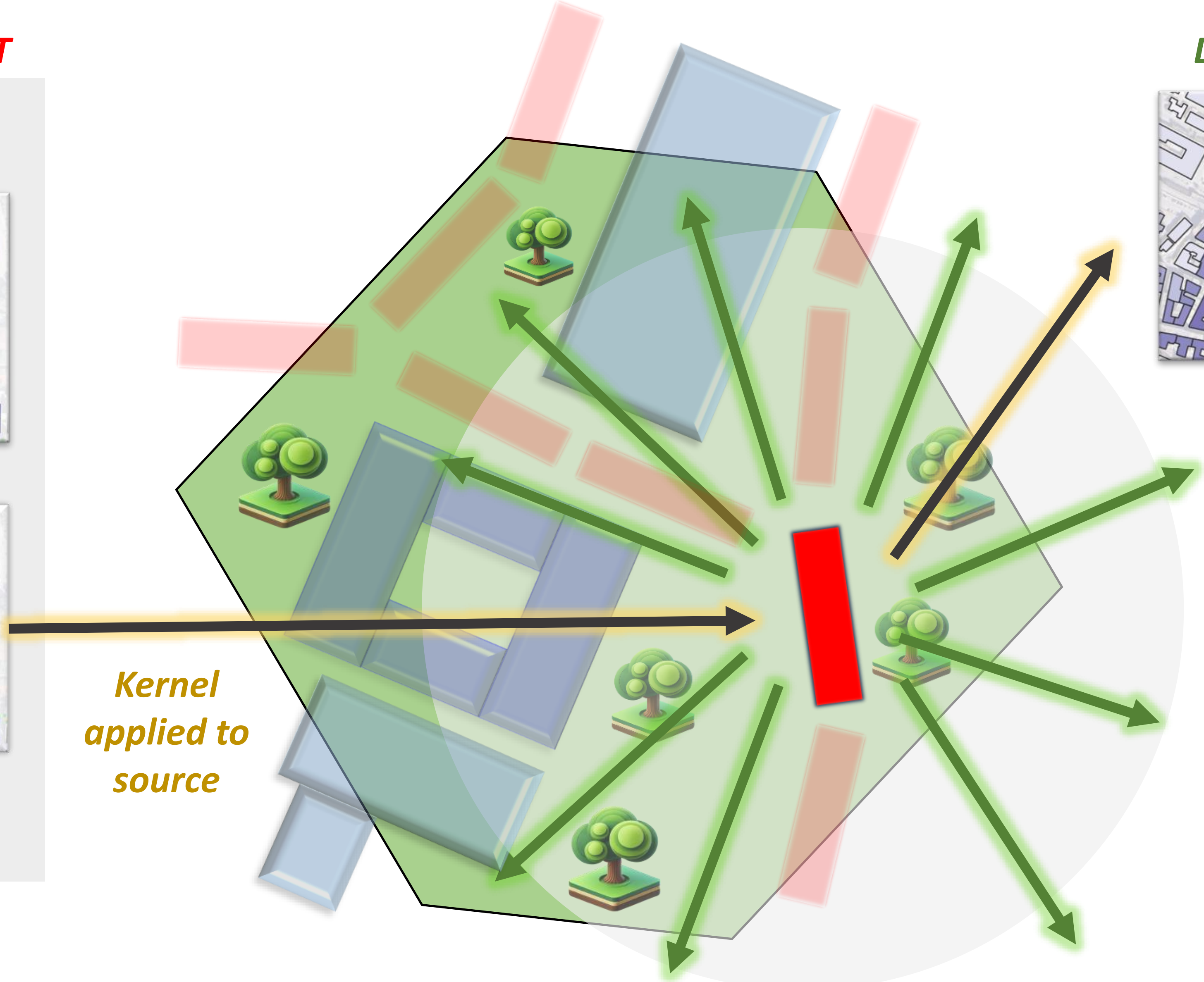
Nature based solutions integrated in the modelling framework

AERODYNAMIC EFFECT

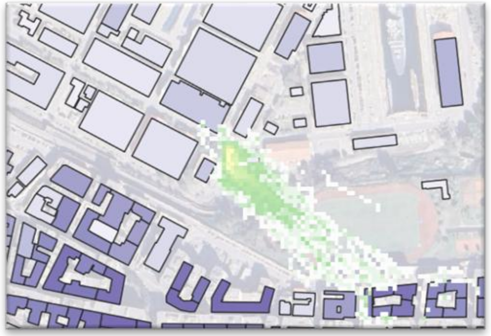
Original Windspeed
7 m/s

Reduced windspeed
3 m/s

Kernel applied to source

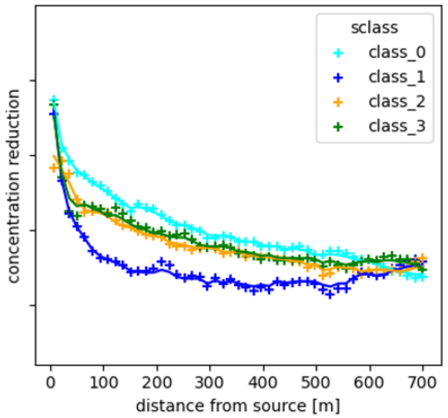


DEPOSITION EFFECT



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.

Nature based solutions integrated in the framework

PM10 annual mean concentration

PM10 annual mean concentration diff (With NBS – Without NBS)

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

THANK YOU

ARIANET

BACKUP SLIDES

ARIANET

Dispersion kernels at microscale – meteo combinations

Dispersion kernels are realized performing 3D **PMSS** simulations for each **combinations** of inlet meteorological variables*

Stationary regime
Normalized emissions

Variable	Number of classes	Classes
Wind direction [degrees from North]	**8**	0° - 45° - 90° - 135° - 180° - 225° - 270° - 315 °
Wind speed at 10 m [m/s]	**6**	1 – 2 – 3 – 5 – 7 – 9
Atmospheric stability class [Pasquill]	**5**	A – B – C – D – E/F

For each meteorological combination, we extract the contribution of each **source** to the **ground concentration field** in a ***square buffer of side 2km*** around the segment baricenter

Total meteo combination: 8 x 6 x 5 = **240**
Sources number: around **26000**

about **6 millions** kernels
(concentration field at ground for street segment and meteo combination)

The kernel database built in such way weights about **180 GB**.

Dispersion kernels at microscale – examples

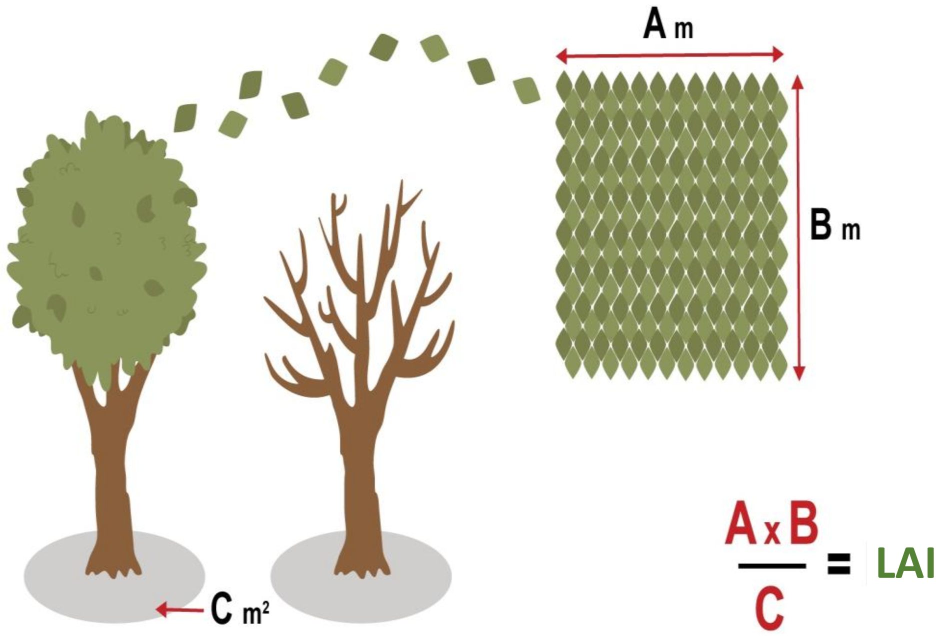
Kernel examples, with **fixed source** e by **varying of meteorological conditions***

* Fields cropped in a domain 600x400 m around a source are displayed to highlight the plume at the source, but kernels extend by 2000x2000 m
Buildings are displayed in purple scale, with intensity proportional to height

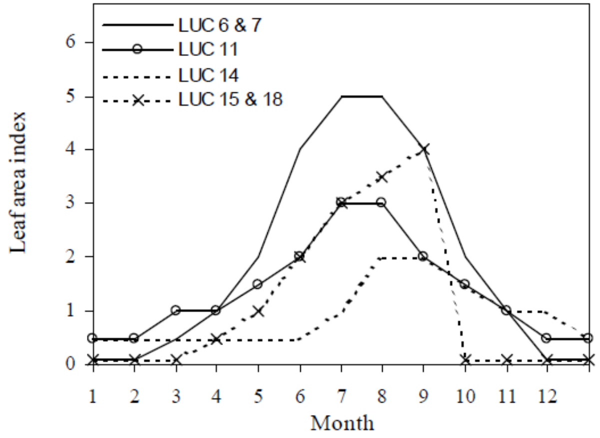
Leaf Area Index

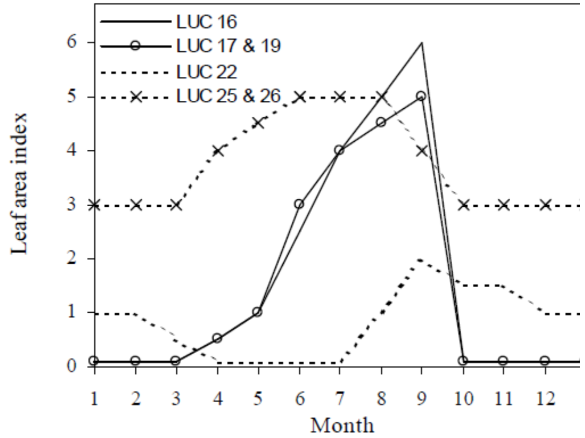
LAI (Leaf Area Index) is a key variable in the parametrization of both the effects

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**

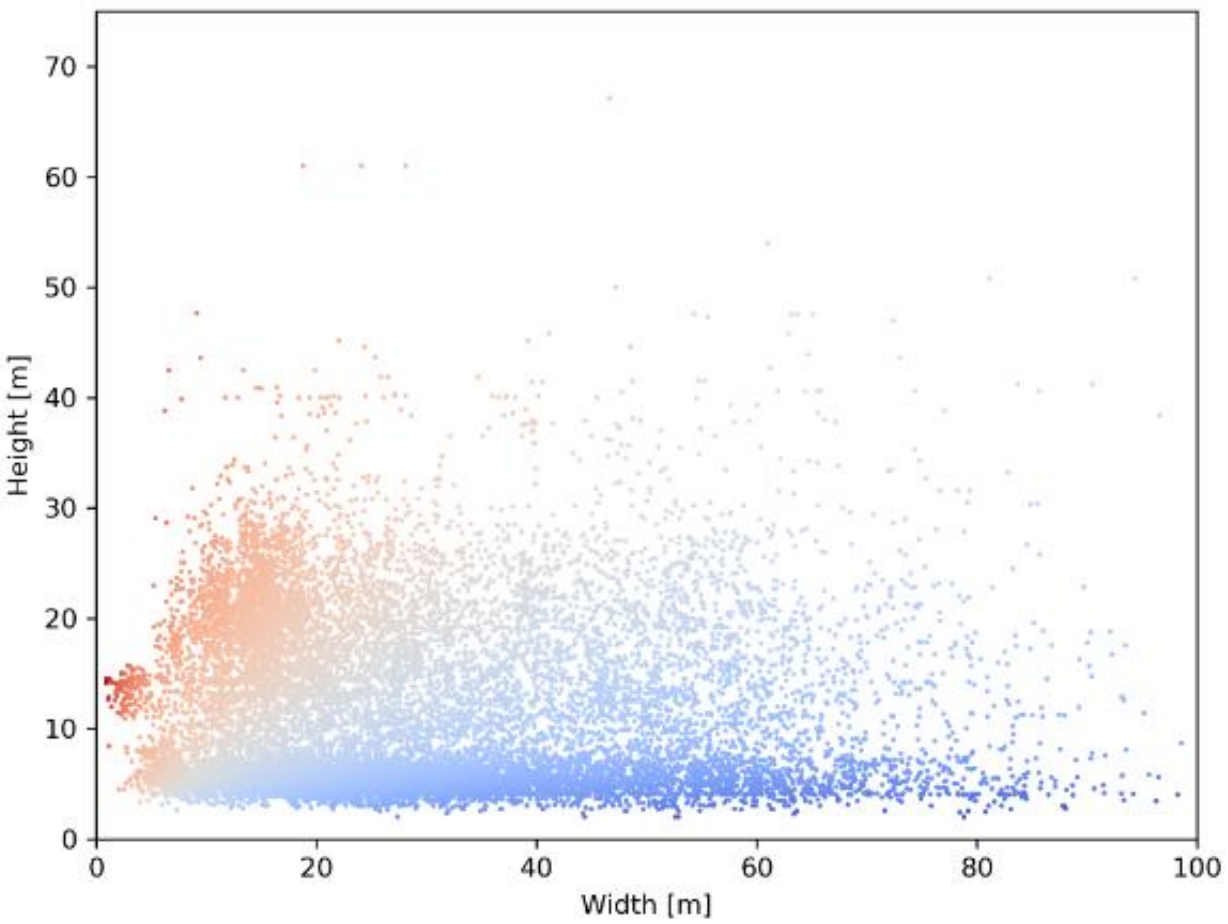
$$z_0 = 0{,}06\, h_{tree}\, \rho_{tree}$$

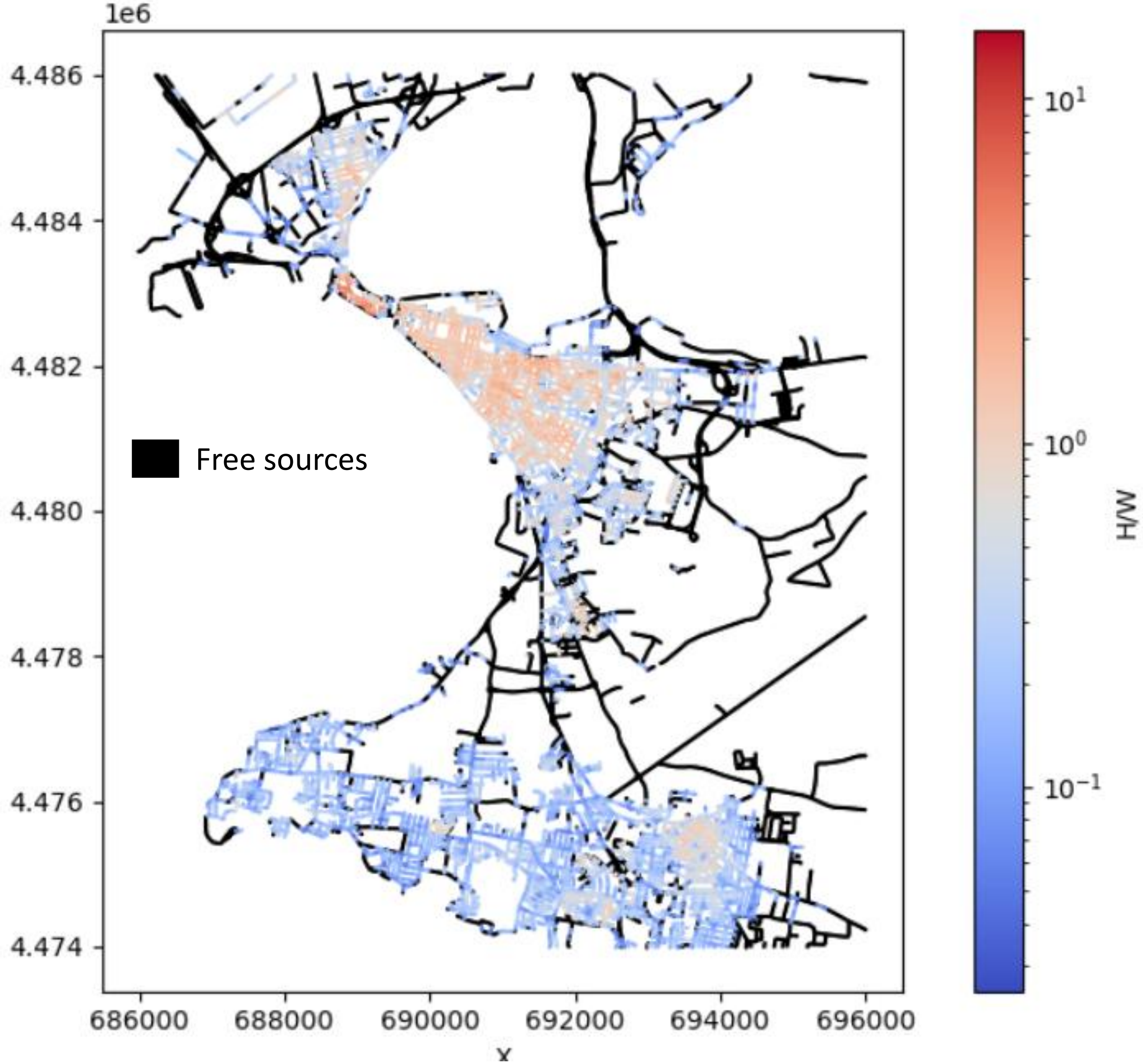
$$LAI = LAI_{min} + (LAI_{max} - LAI_{min}) \frac{z_0 - z_0^{min}}{z_0^{max} - z_0^{min}}$$

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

Aerodynamic effect – Road types in Taranto

Distribution of canyon deepness

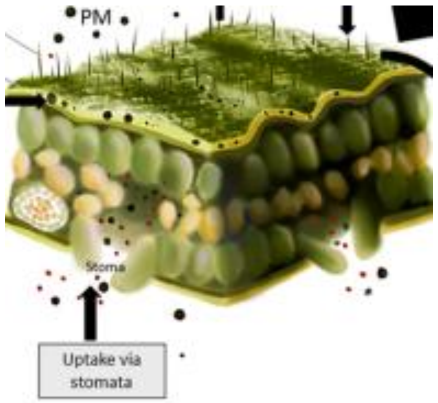


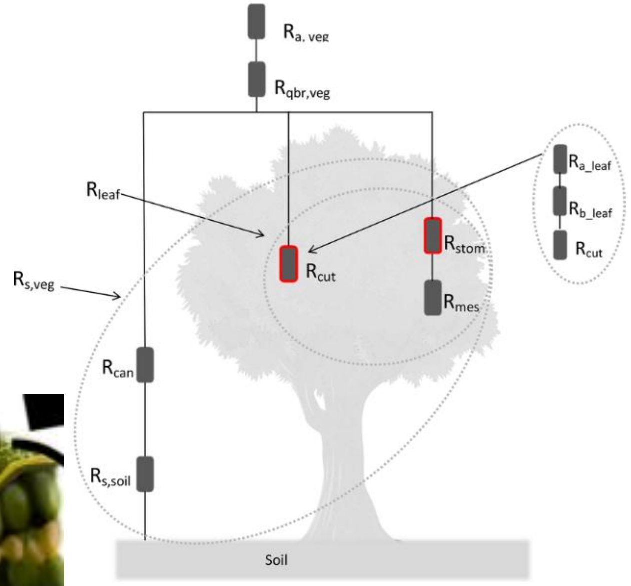


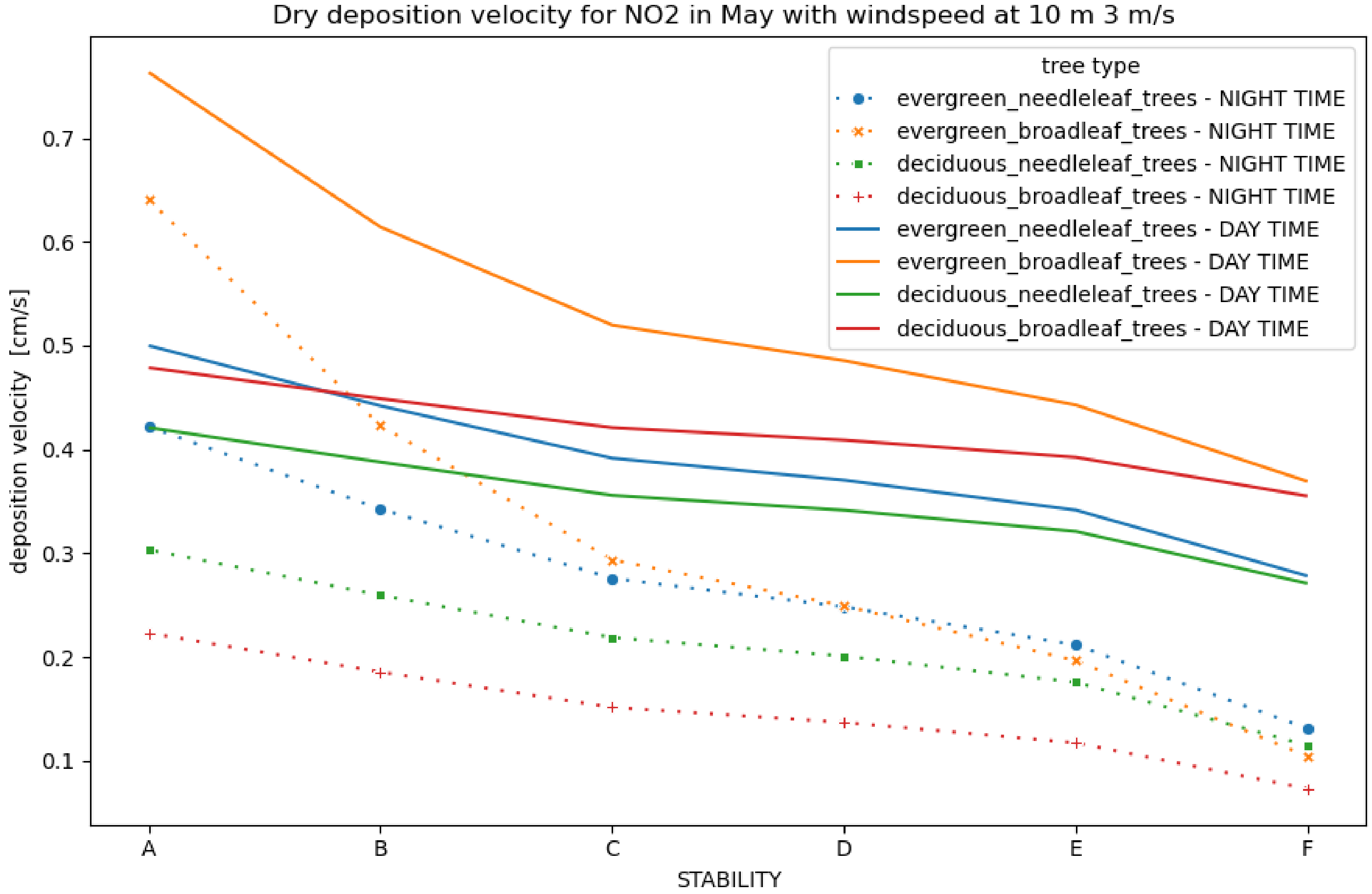
Dry deposition on leaves – gases

For **gases**, the **stomatal resistance** becomes fundamental, namely the capability of gases to entere the stomata of leaves.

In the model, this translates in a dependency on **solar radiation** and thus on **diurnal cycle**, since stomata are closed at nighttime.







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

Natural based solutions – dry deposition effect in CoKer

Derivation of LAI geometric effect $f(LAI)$ = in $R(d) = \frac{e^{-\alpha d}}{(1+\beta d)^{\gamma}} f(LAI)$

$$\frac{dM}{dt} = -C v_d S(LAI)$$

$S(LAI)$ is the total surface of leaves in a ground cell

$$dM = -\frac{M}{S_0\, h_1}\, v_d\, S_0\, \frac{LAI}{h_{tree}}\, h_1\, dt$$

h_1 is the height of the first level cell, S_0 the cell horizontal surface.

$$log(\frac{M}{M_0}) = -\frac{v_d}{h_{tree}}\, LAI \int_0^d \frac{dd'}{U}$$

Assumption "ballistic flow": the concentration and leaves at the other levels do not have an effect on the ground. The flow moves with constant "plume advection speed" U, so that a distance dd is covered in a time $\mathrm{dt} = \mathrm{dd}/U$

$$M = M_0\, exp(-LAI\, \frac{v_d}{U}\, \frac{d}{h})$$

$$R = R_0\, exp(-LAI\, \frac{v_d}{U}\, \frac{d}{h})$$

→

$$f(LAI) = \frac{R(LAI)}{R(LAI=0)} \approx exp\left[(1 - LAI)\frac{v_\mathrm{d}}{U}\frac{d}{h}\right]$$

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