ON THE INFLUENCE OF TREES ON VENTILATION OF A REAL STREET IN PAMPLONA (SPAIN)

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INTRODUCTION AND OBJECTIVE

- Trees and green infrastructures in general are often used in the urban environment as pollution mitigation strategy. However, the impact of urban vegetation on air quality, in particular in streets, is quite complex.
- Main effects of urban vegetation on air quality: aerodynamic effects (i.e. the presence of trees modifies wind flow around them changing the distribution of pollutants) and deposition effects (i.e. a fraction of pollutant is removed from the air by means of deposition on tree leaves and absorption through stomata) (Buccolieri et al. 2018).
- Previous studies in a Pamplona's neighbourhood (Santiago et al, 2017a) indicated that the aerodynamic effects of street trees on pollutant concentration are stronger than deposition.
- This study aims to quantify how the street ventilation changes due to the planting of trees with different foliage density. The idea is to get more insight about the relationship among street vegetation, ventilation and pollutant concentration.

STUDY AREA AND SCENARIOS DESCRIPTION

- Study area:
  - A district of Pamplona (northern Spain).
  - Mean building height: 20 m approximately (ranges from 11 m to 51 m).
  - Vegetation:
    - Area projected in a horizontal plane respect to the total plan area of streets and squares is 13.8%.
    - Mean height of trees ranges from 5 m to 12 m (see Fig. 1).
    - Deciduous trees. Low foliage (LAD= 0.1 $m^2 m^{-3}$) was considered in March.
- Several scenarios (real and virtual) investigated by CFD modelling (Table 1).
- In a real free-tree street (STREET A), several scenarios were simulated assuming new virtual trees, which are located in the center of the street and their crowns located at the same height (from 4 m to 10 m tall).
- A case of bad air quality conditions were selected corresponding to the early morning (8 am) of an average day of March 2015 (high concentrations of NOx occurred).
- Typical meteorological conditions (prevailing wind direction (Northwest) and average wind speed) at this hour were computed from meteorological data recorded at a nearby station.

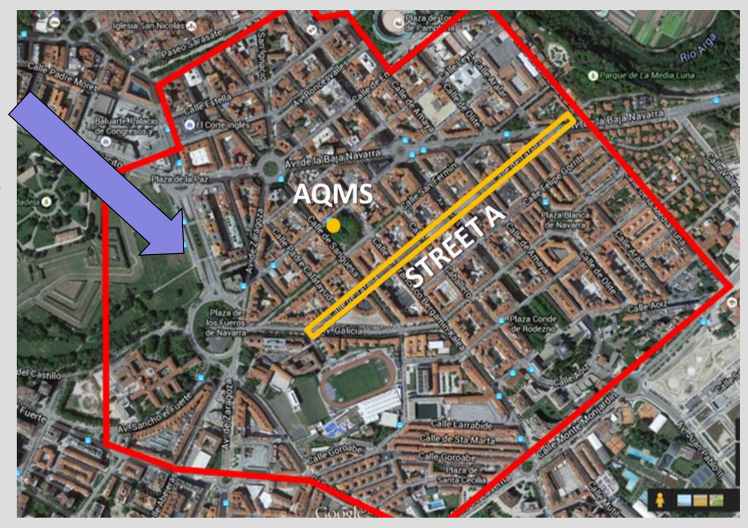

Fig. 1. Study area. AQMS is the location of an air quality monitoring station. In yellow, the tree-free street where different scenarios with different type of trees are simulated

Trees LAD ($m^2 m^{-3}$)	Location of Vegetation	Wind Direction
0.1 (deciduous)	Current location in neighbourhood	Northwest (prevailing wind direction, March 2015)
0.5 (evergreen)		
0.1(deciduous)	Current location in neighbourhood + New trees in STREET A	
0.5 (evergreen)		

Table 1. Studied scenarios. A wide range of deposition velocities induced by vegetation (0, 0.005, 0.01, and 0.03 m s^{-1}) were considered.

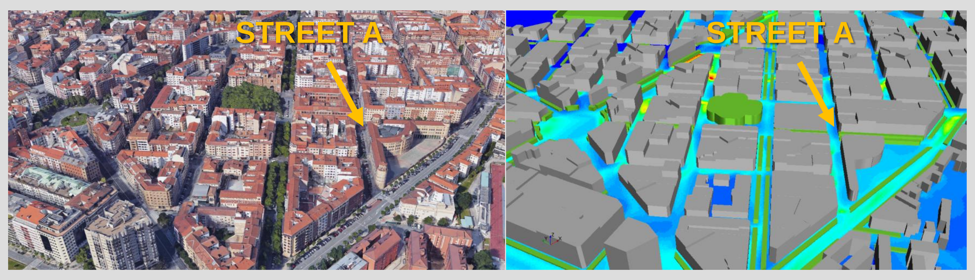

Fig. 2. 3D view of real and modelled study area.

MODEL SETUP

- CFD simulations based on RANS equations with k-ε turbulence closure.
- Tree effects:
  - Dynamic effects: a sink of momentum and sinks/sources in turbulence equations.
  - Deposition: a mass sink proportional to leaf area density and deposition velocity in the pollutant transport equation.
- NOx emissions: Proportional to the daily average traffic intensity of each street. High emissions are located at the main avenue in the North of the district (dashed line in Fig. 3).
- Mesh: Total number of cells is 7.4 x 10^6 with a resolution of 2 m approximately in the center of the district and with refinement close to buildings, ground, emissions and in the narrowest streets (cells of about 1 m).
- Neutral inlet profiles of velocity, turbulent kinetic energy and dissipation are used.
- More details in Santiago et al. (2017a).
- Model Evaluation:
  - Modeled NOx concentrations over the neighbourhood evaluated by using hourly data recorded at AQMS from 1st to 14th March 2015 (Santiago et al., 2017a).
  - Modelling approach previously evaluated against wind tunnel experiments (Krayenhoff et al., 2015; Santiago et al., 2017b).

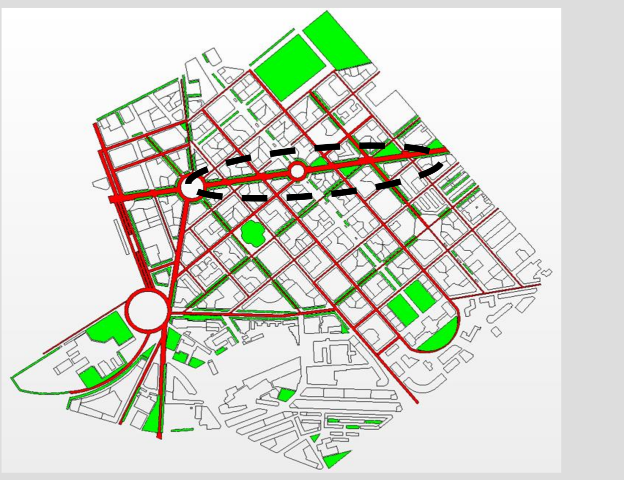

Fig. 3. Numerical domain. Green represents vegetation and red traffic emission zones.

EFFECTS OF STREET TREES ON NOx CONCENTRATION

To analyze the aerodynamic effects, we focus on scenarios without considering deposition.

- For the whole neighbourhood with the current vegetation location, a LAD variation from 0.1 to 0.5 $m^2 m^{-3}$ increases the spatially-averaged concentration at 3 m height by 7.2 %.
- The inclusion of new trees in the STREET A induces changes in average concentrations less than 0.09 % and 0.18 % for LAD = 0.1 $m^2 m^{-3}$ and 0.5 $m^2 m^{-3}$, respectively.
- Focusing on the STREET A, the averaged concentration within this street at 3 m height increases up to 1.3 % as LAD of all neighbourhood trees increases, and by 1.8 % and 12 % when new trees with LAD = 0.1 $m^2 m^{-3}$ and 0.5 $m^2 m^{-3}$ are considered, respectively (Table 2).

Trees LAD ($m^2 m^{-3}$)	Location of Vegetation	Spatially-Averaged Concentration ($\mu g\ m^{-3}$)	
		Whole Neighbourhood	Study street
0.1 (deciduous)	Current location in neighbourhood	105.3	141.9
0.5 (evergreen)		112.9	143.7
0.1(deciduous)	Current location in neighbourhood + New trees in STREET A	105.4	144.4
0.5 (evergreen)		113.1	161.0

Table 2. Spatially-averaged concentrations for eac scenario

- Note that the concentration within STREET A is not only due to local emissions, but there is also a contribution of pollutants released in other streets which is transported.
- Vertical profiles of spatially-averaged concentration over this street are also analyzed (Fig. 4).

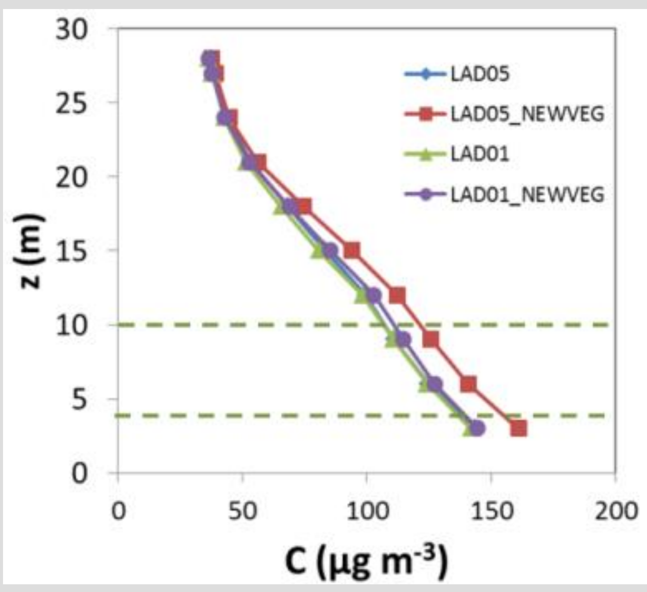

Fig. 4. Vertical profiles of spatially-averaged concentration within STREET A. Dashed lines indicate new trees location.

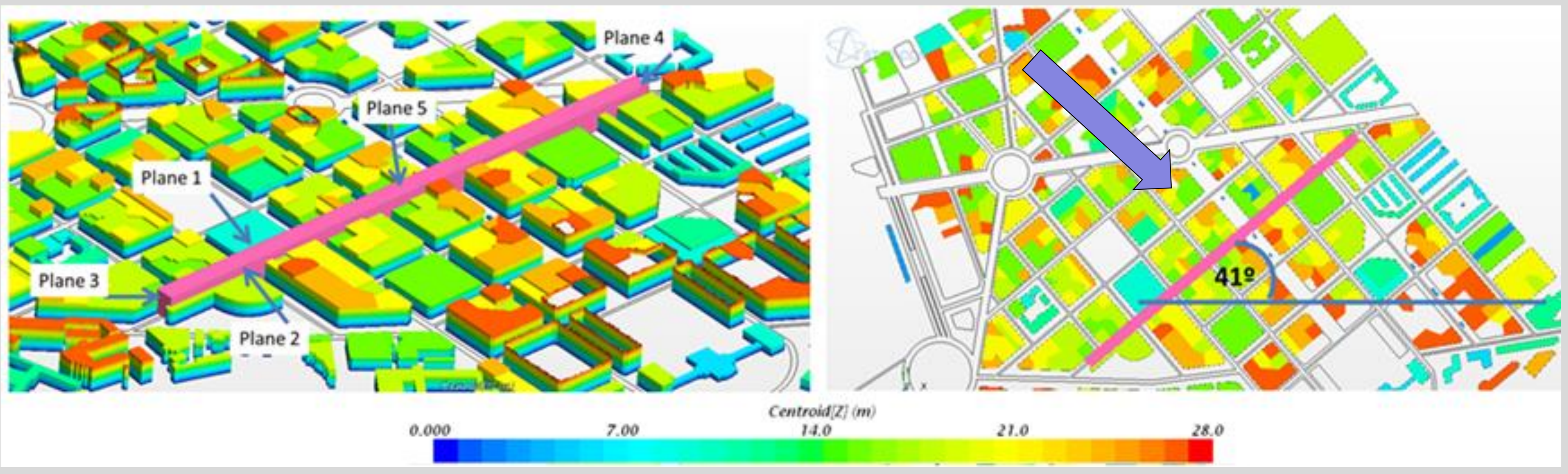

Fig. 5. Planes used for street ventilation assessment (left) and street orientation and wind direction (right).

Trees LAD ($m^2 m^{-3}$)	Location of Vegetation	q (%)				
		Plane1	Plane2	Plane3	Plane4	Plane5
0.1 (deciduous)	Current location in neighbourhood	100	-95.2	-1.1	-0.3	-3.4
0.5 (evergreen)		99.2	-95.1	-1.3	0.8	-3.6
0.1 (deciduous)	Current location in neighbourhood + New trees in STREET A	99.8	-95.2	-0.9	0.2	-3.9
0.5 (evergreen)		99.2	-95.0	-0.8	0.8	-4.2
Trees LAD ($m^2 m^{-3}$)	**Location of Vegetation**	**V_n (m s^{-1})**				
		Plane1	Plane2	Plane3	Plane4	Plane5
0.1 (deciduous)	Current location in neighbourhood	1.49	-1.63	-0.33	-0.08	-0.04
0.5 (evergreen)		1.47	-1.62	-0.40	0.24	-0.04
0.1 (deciduous)	Current location in neighbourhood + New trees in STREET A	1.50	-1.65	-0.26	0.06	-0.04
0.5 (evergreen)		1.48	-1.62	-0.23	0.25	-0.05

Table 3. Percentage at each plane of the total flow rate and average perpendicular velocity to each plane for all scenarios.

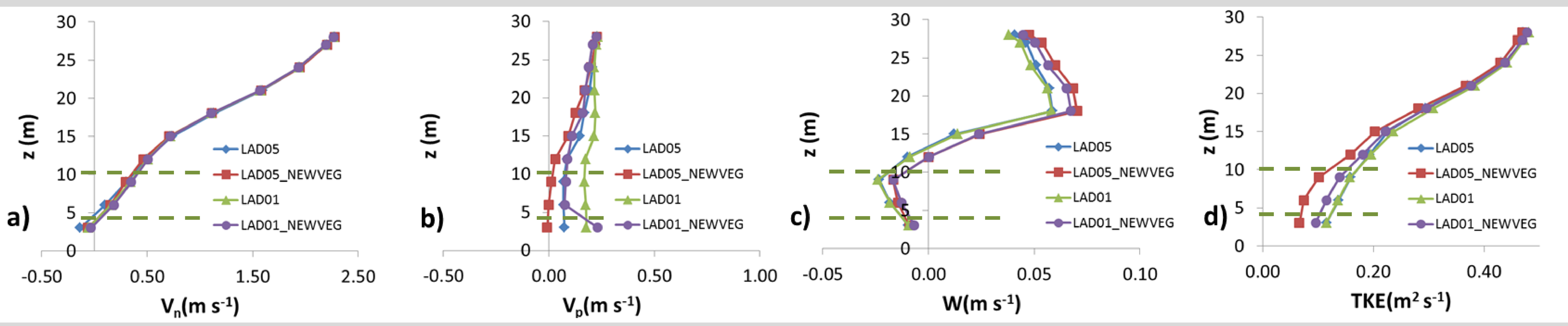

Fig. 6. Vertical profiles of average flow properties over the study street. a) wind speed normal to street (V_n); b) wind speed parallel to street (V_p); c) vertical wind speed (W); and d) turbulent kinetic energy (TKE). Dashed lines indicate new trees location.

VENTILATION ASSESSMENT IN STREET A

- STREET A was assumed as a prism composed by 4 lateral planes (Planes 1-2 parallel to the street and 3-4 perpendicular to the street) and a plane in the top (Plane 5). Plane 5 is located 1 m above the height of the tallest building (z = 28 m) (Fig. 5).
- Wind flow is from Northwest which is almost perpendicular to street orientation (Fig. 5), and then, the most part of flow enters into the street through Plane 1.
- The average flow rate q was computed at each plane following: where V_n is the velocity perpendicular to each plane.

$$q = \int_{PLANE} V_n dS$$

- In Table 3, the percentage at each plane of the total flow rate which enters in the street is shown. Negative values indicate flow direction is towards outside the street (i.e. air leaving the street).
- The higher tree LAD, the higher concentrations in the whole neighbourhood due to the decrease of average velocity normal to Plane 1.
- The new trees configuration affects the flow rates and the normal velocities (Table 3):
  - Reduces the average flow rate in the parallel direction increasing it at the top plane.
  - Modifies the flow rate at the perpendicular planes to street direction (3 and 4). For LAD = 0.5 $m^2 m^{-3}$, the flow outward the street decreases up to 40 % approximately for plane 3. However, these average values are not representative for the whole street. Due to street intersections, there are parts of the street with horizontal vortices and others with channeling in different directions.
- The new trees configuration modifies vertical profiles of average wind flow properties (wind speed normal to street (V_n) and parallel to street (V_p), vertical wind speed (W) and turbulent kinetic energy (TKE)) in STREET A (Fig. 6):
  - Average parallel wind speed decreases for new vegetation scenarios, especially within and below the vegetation canopy.
  - Concerning vertical wind speed, downward wind speed within and below the vegetation canopy is lower for new vegetation scenarios, while upward wind speed over the new trees is stronger with vertical velocity at the top of street higher than for scenarios with no trees in STREET A.
  - A decrease of TKE within vegetation canopy is clearly observed.
  - These processes are stronger for new trees configuration with LAD = 0.5 $m^2 m^{-3}$.

CONCLUSIONS

In the whole neighbourhood, average concentrations increases and average wind speed is lower when LAD increases.
Within the STREET A, new trees induces an increase of average concentration (specially with high LAD) because:

- average wind speed parallel to the street (parallel ventilation) is reduced;
- downward wind speed within new vegetation canopy is reduced (weaker ventilation) within and below the vegetation canopy, while upward wind speed slightly increases over the trees (more ventilation)
- TKE decreases within and below new vegetation canopy.

These results could be useful for urban planners to build sustainable design of vegetation within streets, although local effects within the street should also be taken into account.

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