Urban vegetation effects on meteorology and air quality: a comparison of three European cities

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Abstract

Nature based solutions (NBS) have been put forward as an effective approach for improving human well-being in the cities during the last decade and many of them make use of vegetation (trees, grass, etc). The role of vegetation in regulating air temperature and moisture availability is recognized together with its capacity to remove pollutants. Yet, cities lack of quantitative evaluation of these effects that may set the basis for the assessment of the impacts of new NBS. This study conducted within the framework of Life VEG-GAP project shows the impact of vegetation on temperature and, further, on air concentrations and deposition of ozone (O_3), particulate matter (PM10) and nitrogen dioxide (NO_2) in three European cities: Bologna, Madrid and Milan. The simulations were carried out with two state-of-the-art air quality modelling systems using the same meteorological model WRF with building effect parametrization (BEP) to account for the differences in urban morphology, but different chemical transport models (CTM): CMAQ for Madrid and FARM for Bologna and Milan. The emissions of biogenic volatile organic compounds (BVOC) were produced with the same species-specific model, called PSEM. The simulations were carried out over several nested domains from European to city level where the spatial resolution was 1 km^2. The results show that vegetation effects on air temperature, pollutant concentrations and depositions depend on the characteristics of the city (morphology, geographic location and size), of the vegetation (extension and species) and on local chemical conditions (the cocktail of anthropogenic emissions, dispersion conditions, etc.). By applying this one-atmosphere approach for vegetation-meteorology-chemistry, the combined effect of pollutants removal, BVOC emissions distribution as well as chang-

es of wind patterns, temperature, etc., leads to contrasting time-dependent variability patterns of vegetation effects across the cities.

Introduction

Urban vegetation provides many ecosystem services which influence the atmospheric processes responsible for air quality and climate variations. In addition to its direct benefit for the human well-being by offering opportunities for outdoor recreation, education, socialization, etc., green spaces indirectly contributes to human health by changing the air temperature and chemical composition. This study shows for the first time how the current vegetation affects the urban environment, quantifying its contribution to thermal comfort and air quality, in three European cities, Bologna, Madrid and Milan, for a summer day during anticyclonic weather conditions.

Materials and methods

The effect of vegetation on temperature, air concentration and deposition of ozone (O_3), particulate matter (PM10) and nitrogen dioxide (NO_2) was evaluated with state-of-the-art air quality modelling systems (AQMS) since they are the only tools able to assess the effects of vegetation on the atmosphere in a comprehensive and realistic manner and are largely used to support Air Quality Plans at regional and local levels as well as at national level in support to NEC Directive.

The simulations were carried out over the cities at 1 km^2 spatial resolution and were nested in simulations over European and national/regional domains. Two AQMS were used, the Atmospheric Modelling System of MINNI project (AMS-MINNI; Mircea et al., 2014, 2016) for Italy and WRF-SMOKE-CMAQ (Borge et al, 2008) for Spain. AMS-MINNI is composed of the meteorological model WRF v3.9.1.1 (Skamarock and Klemp, 2008), the emission processor EMMA (Emission MAnager, ARIA/ARIANET, 2008) and the chemical transport model (CTM) FARM (Flexible Air Quality Regional Model, Silibello et al., 2008). The Spanish AQMS uses WRF v4.1.2, the Community Multiscale Air Quality (CMAQ) CTM (Byun & Schere, 2006) and the emissions processor SMOKE (Sparse Matrix Operator Kernel Emissions).

The simulations at European and national/regional scales were made by ENEA and UPM using same anthropogenic emission inventory, CAMS-REGAP_v2.2.1, provided by TNO for 2015. Boundary conditions for meteorological and chemical conditions at European scale were recovered from European Centre for Medium-Range Weather Forecasts (ECMWF) and, respectively, from CAMS Copernicus platform. The validation of simulations used observations from European Environment Agency and from national/regional/local environmental agencies. Emissions from Spanish sources in the nested domains are a combination of different official emission inventories: the National Emission Inventory (MITECO, 2019) and the local emission inventory of the Madrid City (AM, 2019). The national emission inventory distributed by ISPRA (Italian Institute for Environmental Protection and Research) with provincial level (NUTS3) detail (where NUTS stands for Nomenclature of territorial units for statistics, the hierarchical system for dividing up the territory of the European Union) was used for the Italian domain, while local emission inventories provided by Regional Environmental Agencies (ARPA) of Lombardy and Emilia Romagna Regions were used for Milan and Bologna. All the simulations used biogenic volatile organic compounds (BVOC) emissions produced with PSEM model (Silibello et al., 2017). BVOC emission fluxes were computed using vegetation maps built from the tree inventories provided by the partner municipalities and from ancillary information on the regional forest cover, complemented by European reference CORINE land cover.

The effect of current vegetation on atmospheric characteristics was estimated as the difference between a simulation with vegetation (SVR –simulation vegetation real) and a simulation without urban vegetation (SVN –simulations vegetation null). However, SVN did not exclude the peri-urban forests located in the Northern part of Madrid (Cuenca Alta del Manzanares Regional Park) and in the South-Eastern part of Bologna (Colli Bolognesi) respectively, as well as the agricultural area located south and west of Milan (Parco agricolo sud). The CTMs and meteorological model used the same approach for both scenarios: the vegetation was replaced by bare soil only in the urbanized area of the city. The CTM simulations included all the detailed information on vegetation cover extension and characteristics, the effect of vegetation on meteorology and detailed species-dependent BVOC emissions.

Results

Figs. 1 and 2 show the differences between SVR and SVN simulations for the domains including the cities with a spatial resolution of 1km^2. The cities are located approximately in the middle of the domain to avoid significant impact of the boundary conditions. The negative values indicate a decrease of temperature, concentrations and dry depositions due to vegetation and the positive values indicate the opposite. Differences in temperature and concentrations are shown as daily averages while in depositions and BVOC emissions are shown as daily totals. In the three cities, the actual vegetation has a cooling effect but its magnitude and extension varies inside/around the city core and among the cities (Fig. 1). The temperature is reduced more than 0.5 ^{o}C in some areas of Madrid and Milan but below 0.4 ^{o}C in Bologna. As expected, there is no cooling in the areas of peri-urban forests of Bologna and Madrid since their effect was not investigated while a low decrease of temperature is observed south-west of Milan. Increases of temperature observable mainly outside the conurbation boundaries can be attributed to the variation of local atmospheric circulation induced by the urban vegetation and generally show transient features with different space location in different days.

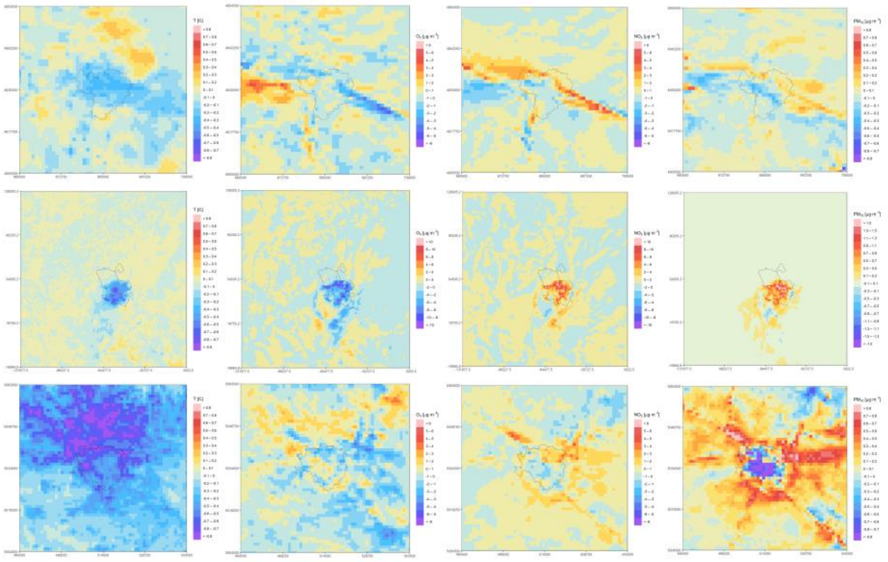

Fig.1. Differences of daily average (SVR-SVN) temperature (^{o}C) (1stcolumn) and air concentrations (μg/m^3) of O_3 (2nd column), NO_2 (3rd column) and PM10 (4th column) for 13 July 2015 and for Bologna (1st row), Madrid (2nd row) and Milan (3rd row).

The decrease of air temperature due to vegetation leads to both increases and decreases of ozone concentrations according to the local chemical composition: the Madrid and Milan areas where O_3 decreases correspond to an increase of NO_2 and PM10, possibly due to the reduction of wind speed induced by vegetation. The opposite effect also occurs. In Bologna, a substantial decrease of O_3 is observed mainly along A14 highway while in the other two cities the decrease is not so clearly related to traffic emissions. For all three pollutants, the differences in concentrations vary among the cities, with the highest changes observed in Madrid. This effect and the small variations observed outside of the cities are due to meteorology changes associated to vegetation removal. The highest differences in the BVOC emissions and dry deposition patterns due to the overall vegetation cover is observed within the city limits except for the O_3 in Bologna (Fig. 2). For all three cities, the amount of pollutants removed by dry deposition is higher for O_3 than for NO_2. The highest amount of PM10 is removed in Milan while comparable values are observed in the areas of Bologna and Madrid. The magnitude of differences for all pollutants is characterised by positive values substantially higher than the negative ones pointing out that the efficiency of vegetation in filtering the air locally is more important than the negative effects due to changes in meteorology and BVOC emission. However, in all the cities, the combination of meteorological changes with perturbations of local chemistry as well as with urban morphology leads also to areas where SVR dry deposition is lower than that for SVN. Interesting to note similarities in emissions and deposition pattern driven by vegetation cover for a given city and differences among cities.

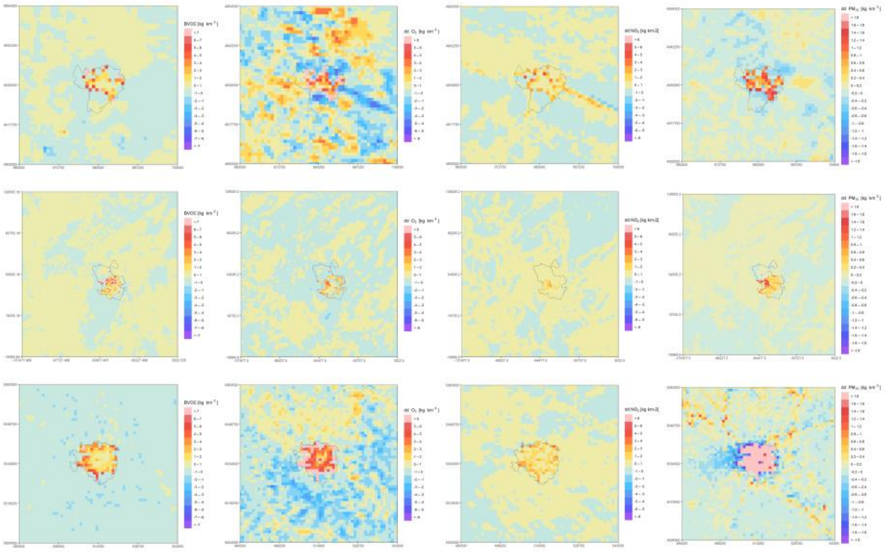

Fig.2. Differences (SVR-SVN) of daily sum of BVOC emissions (kg/km^2) (1st column) and of dry depositions (kg/km^2) of O_3 (2nd column), NO_2 (3rd column) and PM10 (4th column) for 13 July 2015 and for Bologna (1st row), Madrid (2nd row) and Milan (3rd row).

Moreover, deposition patterns vary with pollutant type since the deposition models for gases and particulate matter use different approaches to evaluate interactions with vegetation.

Conclusions

The coherence among AQMSs' results in different cities rei their capacity to support air quality and urban planning decision processes that include both vegetation increase and anthropogenic emissions reductions. It also points out the necessity to couple the assessments of air quality with the changes in the meteorological conditions induced by new interventions in urban structure. AQMSs may also support a deeper understanding of the differences in temperature, air concentrations and deposition of pollutants such as ozone (O_3), particulate matter (PM10) and nitrogen dioxide (NO_2) inside and around the cities due to urban green.

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