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*Research article*

# Quantifying the local-scale ecosystem services provided by urban treed streetscapes in Bolzano, Italy

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**Abstract:** Urban green infrastructure has the potential to offer multiple ecosystem services to society. However, there is little information about the role of these tree dominated, public streetscapes on the local-scale provision of ecosystem services in European mid-sized cities. In the present study, we explored the local-scale effects of different tree dominated streetscape types on mitigating temperatures and air pollution in the city of Bolzano, Italy by integrating the ENVI-met and UFORE models as well as local field, pollution and climate data. We found that total estimated air pollution removal by trees in Bolzano was 2.42 metric tons per year (t/yr); with ozone (1.2 t/yr) being the pollutant most removed and carbon monoxide (0.03 t/yr) the least. Total air pollution removal (901.4 kg/yr) was greatest in parks. Total biogenic volatile organic compound emissions, an ecosystem disservice, were also estimated. The ENVI-met simulations found that urban trees can reduce streetscape temperatures by up to 2 °C during the summer and improve human thermal comfort. Results can be used to better understand the dynamics of local-scale ecosystem services of mid-size European cities and to better assess the role of urban streetscapes and green infrastructure in improving human well-being and mitigating the effects of climate change.

**Keywords:** Air pollution; ENVI-met model; ecosystem disservices; thermal comfort; green infrastructure

## 1. Introduction

Increased urbanisation is altering natural and semi-natural ecosystems, causing the loss of vegetation, biodiversity, open spaces, and changing both hydrologic and biogeochemical cycles [1]. For example, average temperatures in large metropolitan areas of 100,000 to 1 million people can be 5–10 °C warmer than surrounding rural areas and results in urban heat island (UHI) effects [2-4]. Incidences of longer and warmer summer temperatures are also increasing and this is likely due to climate change [5]. These increased temperatures are resulting in increased mortalities during summer heat waves [6-9]. Indeed a number of health and environmental issues are arising from these altered ecosystems. Thus effective planning strategies for the urban environment are needed to improve the local-scale climates and to provide other multiple benefits, such as energy savings and the reduction of health risks [10].

In human-modified urban ecosystems, urban green infrastructure plays a key role in improving the aesthetics, environment, and the overall quality of life of its residents. Urban green infrastructure is a hybrid infrastructure of green spaces and built systems, e.g. urban forests, wetlands, parks, green roofs and walls that together can contribute to ecosystem resilience and human benefits through ecosystem services [11]. As such, urban green infrastructure has been documented as providing several economic, aesthetic [12-14], cultural [15,16] and architectural benefits [17]. In particular, urban green infrastructure provides multiple ecosystem services and goods, such as urban air quality improvement [18-21]. It can also regulate climate through carbon storage and sequestration [22,23] as well as offset carbon dioxide ($CO_2$) emissions from cities [24-27]. Green infrastructure can also improve human thermal comfort through altering the albedo of surfaces as well as cooling atmospheric temperatures through shading and evapotranspiration [28-33]. As the rate of urbanization of the world's population continues to increase, urban woody vegetation in particular will be one of the primary components of green infrastructure [34].

These ecosystem services from green infrastructure are important since they can have direct tangible, benefits by improving human health [35,36]. For example, air quality improvement by urban vegetation can reduce health problems and mortality [37-39]. Other epidemiological studies that control for age, sex, marital and socio-economic status, have provided evidence of a positive relationship between green space and the life expectancy of senior citizens [40-42]. In Milan, Italy Picot (2004) [43] investigated the thermal comfort provided by trees in an Italian piazza and found that the shading effect under a mature tree canopy shows a reduction of the absorbed radiation, generating an energy budget very close to acceptable human comfort (under 50 $W/m^2$). Lafortezza, Carrus, Sanesi, & Davies, (2009) [44] found that longer and frequent visits to green spaces generate significant improvements of the perceived benefits and well-being among users. According to Armson et al. (2012) [45] tree shade can reduce surface temperatures by up to 19 °C in an urban area. More recently, at the local-scale, Maher et al. (2013) [46] documented a 50% reduction in particulate matter levels inside houses that were screened by street trees in the United Kingdom.

Recent studies have demonstrated that urban green spaces can also result in decreased well-being or ecosystem disservices [19], such as costs to the community including social problems (e.g. fear of crime), health problems (e.g. increasing allergy from pollen), environmental problems (e.g. volatile organic compounds—VOCs), and economic disadvantages such as, e.g. maintenance costs of urban forests [19,47]. Thus, the ecosystem services concept provides useful benchmarks and performance indicators to link science with urban planning policies and design alternatives [48]. A

key similarity across these studies is the importance of accounting for scale and costs when quantifying urban ecosystem service provision [19].

Several approaches for mapping and assessing urban ecosystem services exist, however once again they are generally made at the regional or city-wide scales [47,49,50]. Within a city, because of scale and context issues- and the importance of human well-being- there is a need for ecosystem services quantification and assessments at the local scale and including more than one ecosystem service (i.e. a bundle or stacked ecosystem services) in order to be useful for policy and planning purposes [19]. Recently, ecosystem services of urban green infrastructure have been assessed using available methods including computer models such as ENVI-met, i-Tree (i.e. Eco/UFORE, Streets), and in the past CITY green [47,51,52]. These models have been developed or adapted for landscape design and urban planning [53].

For example, most of the above studies have been developed in the United States (US) [47] with relatively few in Italy or the rest of Europe [35]. Relevant studies from Italy have examined specific ecosystem services provided by urban green spaces and urban trees. Siena & Buffoni (2007) [54] examined the air quality improvement of a small park in Milan, while others have focused on city-level ozone ($O_3$) removal [55,56]. Papa et al. (2012) [57] analysed trace metal concentrations (Pb, Cd, Cr, Ni, V and Cu) in *Q. ilex* leaves sampled in different sites of Caserta, Southern Italy. Other studies by Gratani & Varone (2007) [58] and Baraldi, Rapparini, Tosi, & Ottoni (2010) [59] and Russo et al. (2014) [60] have quantified $CO_2$/carbon sequestration at the species level, and social aspects have been studied by Sanesi & Chiarello (2006) [61] and Secco & Zulian (2008) [62]. Again, most studies on air pollution removal were largely based on modelling work at the city or large park scale [35].

The above literature also shows that few studies in Italy and Europe have examined the bundle of ecosystem services provided by urban treed streetscapes [47,63-65]. More specifically, there is little information about the local-scale ecosystem services provided by urban green infrastructure in mid-sized cities in the Southern Alps and Northern Italy. According to Konijnendijk et al. (2013) [35], studies on trees and air quality improvement have emphasized multiple sites and not specific green spaces or local-scale areas such as individual parks.

Therefore, the overall aim of this study was to develop an integrated local-scale methodology to quantify a bundle of key ecosystem services provided by urban trees in different streetscape types using: biometric data, site-specific meteorological and pollution concentration data, integrating two simulation models (Urban Forest Effects and ENVI-met), and an existing tree inventory with ancillary spatial data. Our specific study objectives were to estimate at both the individual tree and streetscape scales: (1) the mitigation role of urban trees on streetscape-scale temperature and human thermal comfort, (2) the removal of ozone ($O_3$), particulate matter less than 10 microns, ($PM_{10}$), nitrogen dioxide ($NO_2$), and carbon monoxide (CO), and (3) the biogenic emissions of these trees as a proxy for quantifying the ecosystem disservices of these streetscapes in a northern Italian city.

Results from this approach can be applied towards Action 5 of the European Union Biodiversity Strategy, that requires Member States, with the assistance of the Commission, to map and assess: the state of ecosystems and their services in their national territory by 2014, the economic value of such services, and promote the integration of these values into accounting and reporting systems at EU and national level by 2020 [49,66]. Furthermore, according to European legislation on air quality, the Member States should undertake assessments of air pollution levels using measurements and modelling and other empirical techniques. Where pollution levels are elevated, the Member States

should prepare an air quality plan or program to meet such standards [67].

## 2. Materials and Method

### *2.1. Study area*

This study was conducted in the city of Bolzano in the autonomous region of Trentino-Alto Adige/South Tyrol in northern Italy (46°29'28" N, 11°21'15" E). Bolzano has a population of approximately 100,000 inhabitants and covers an area of over 50 square kilometres [68]. Green areas represent about 3.9% of the city's territory which accounts for approximately 20 square metres of green space per person [69] and the city has an estimated urban tree population of 12,000 trees [70]. According to the Köppen classification Bolzano's climate type is moist continental "Dfb" characterized by cold winters and warm summers with no marked dry seasons with mean annual precipitation of 740 mm and a mean average maximum and minimum temperature of 17.9 °C and 6.8 °C, respectively [71]. In 2010, the City of Bolzano prepared an air quality plan for nitrogen dioxide ($NO_2$) reduction as required by the European Union Air Quality Directive (Directive 2008/50/EC) [67]. The area in Bolzano where $NO_2$ concentrations exceed the limit values has an extension of about 3.4 square kilometres with a population of about 25,000 people. The highest concentrations of $NO_2$ (62 μg/m³) have been identified along major streets such as the A22 highway Brennero-Verona [72].

In this study, we define "streetscape" as any area with paved roads, street infrastructure, roadside buildings and vegetation [26]. Tree dominated streetscapes are components of a city's green infrastructure and as such are capable of delivering a wide range of previously mentioned environmental, social, and quality of life benefits for local communities [42,53,73]. Russo et al. (2015) [26] has identified six streetscapes types in Bolzano: boulevards, cycle paths, parks, piazzas, promenades, and streets. See Russo et al. (2015) [26] and citation therein for more details on the use of the streetscape approach in other studies.

### *2.2. Ecosystem services quantification at local-scale*

We define local – scale as patches or corridors (tree-lined streets) that have a spatial resolution from about 100 square meters to 1 square kilometer. A principle reason for focusing our analyses at the local-scale resolution relates to hierarchy theory [74-76] since it lends itself to multi-spatial applications and scaling up of our results. For example, our spatial resolution can be applied to not only individual trees and streetscapes but for easily assessing thermal comfort levels of large areas such as an entire city [77].

Further, we followed the definition of Escobedo et al. (2011) [19] for an ecosystem service as the components of urban greening that are directly enjoyed, consumed, or used to produce specific, measurable human benefits such as air quality improvement and thermal comfort. Following Baró et al.'s approach for another southern European city [78], we focused on two measurable ecosystem services ("air purification" and "microclimate regulation") and one ecosystem disservices (Biogenic Volatile Organic Compound (VOC) Emissions). The framework of our methodology is outlined below and consists of four sequential parts: 1) use existing tree inventory data in a Geographical Information System (GIS) format, 2) select and parametrize the appropriate

mathematical, functional and simulation models, 3) field measure streetscapes in order to obtain biometric data required by the models, and 4) apply the output of the simulation model to the tree inventory in order to map ecosystem services as required by the European Commission. The specific methods for quantifying each service are summerized in Table 1.

**Table 1. Methods for quantifying local-scale ecosystem services in Bolzano.**

| Ecosystem Services | Method | Input data |
|---|---|---|
| Air pollutant removal | UFORE outputs of $PM_{10}$, $O_3$, CO, and $NO_2$ removal values by DBH classes have been assigned to Bolzano's tree inventory single tree by DBH class | Species, number of DBHs recorded, DBH (cm) , height to crown base (m), crown width (m), percent canopy missing, dieback, crown light exposure, hourly weather data, hourly pollution data (the concentration of the pollutant in ppm for CO, $NO_2$, $O_3$ and in $\mu g/m^3$ for $PM_{10}$) [79] |
| Temperature reduction | ENVI-met model using aerial photographs, Vector data combined with Bolzano's tree inventory | Wind speed in 10 m above ground (m/s), roughness length z0 at reference point, wind direction, initial temperature atmosphere (K), specific humidity (g Water/kg air), relative humidity (%), walking speed (m/s), heat transfer resistance cloths, building height (m), vegetation and materials information [80,81] |
| Ecosystem Disservices | | |
| Biogenic Volatile Organic Compound (VOC) Emissions | UFORE outputs of isoprene, monoterpenes, and other VOC emissions that contribute to $O_3$ formation | Hourly weather data, species and field data [79] |

UFORE = Urban forest effects model; DBH = Tree stem diameter at breast height (1.37 m above ground surface).

### *2.3. Tree inventory*

Inventories provide data on various ecosystem structural components relevant to these types of assessments. Countries routinely conduct these inventories of their natural resources at regional or continental scales [82]. Consequently, as ecosystem services of urban green spaces are relevant at the local scale, tree-level biometric data such as an urban street tree inventory are particularly useful for assessing these services [79]. The data provided in Bolzano's tree inventory relevant to our modeling approach included species, diameter (cm), height (m), health condition (in classes), streetscape type and global positioning system location (latitude, longitude) [70]. The tree inventory data were from the year 2000 and has been updated every 2–3 years. Year 2000 urban tree stucture data for use in our models requiring the tree inventory were updated to current stem and height sizes using Bolzano's stem growth rates [60] following Russo's (2013) [70] methods.

*2.4. Numerical functional and simulation models*

We used two available models to quantify our ecosystem services of interest. First, we used the Urban Forest Effects (UFORE-ACE-D Version 6.5) air pollution deposition and biogenic emission model because of its previous use at the urban forest-scale in Italy [54,63] and other European cities such as, e.g. Zurich [83]; Barcelona [78,84], London [85], and Torbay [86]. But, rather than analyzing urban forest-scale functions we modeled at the individual tree-scale. Additionally, we integrated this approach with another model and modelled temperature effects at the streetscape scale using the ENVI-met model because of its development and regular applications in Europe [80,81,87].

*2.5. ENVI-met input data and methods*

The ENVI-met (Version 3.1) is a three-dimensional non-hydrostatic model for the simulation of surface-plant-air interactions within urban environments. It is designed for micro-scales with a typical horizontal resolution from 0.5 to 10 m and a typical time frame of 24 to 48 hours with a time step of 10 seconds at maximum. This resolution allows for the analyses of small-scale interactions between individual buildings, surfaces, and plants. Of relevance to this study, the model's calculation includes key processes such as:

- Short-wave and long-wave radiation fluxes with respect to shading, reflection, and re-radiation from buildings and the vegetation;
- Transpiration, evaporation, and sensible heat flux from the vegetation into the air including full simulation of all plant physical parameters (e.g. photosynthetic rate);
- Surface and wall temperature for each grid point and wall;
- Water and heat exchange inside the soil system;
- Calculation of biometeorological parameters like Mean Radiant Temperature or Fanger's Predicted Mean Vote (PMV) Value;
- Dispersion of inert gases and particles including sedimentation of particles at leaves and surfaces [80,81].

In ENVI-met simulations, a plant is defined by its height, leaf-area index (LAI), and its root zone. The LAI is defined as the total one-sided leaf surface area ($m^2$) per unit ground area ($m^2$) [88]. Each plant is divided into ten horizontal layers above-ground, each of which is specified by its leaf-area density (LAD; $m^2/m^3$) [88], where LAD profiles define the crown shape and height of a tree [81]. The LAD is therefore a key parameter used to model radiation transmission through a tree canopy and between a tree and its environment [89]. We chose a site in Bolzano's historic centre for our simulation while the ENVI-met model domain was developed based on the actual geometry of the site using aerial images and vector data from our ancillary spatial data using ArcGIS v10. The ENVI-met parameters were set up according to Bolzano´s streetscape using city-specific data such as climatic information (i.e. wind speed and direction, roughness length; initial temperature atmosphere; specific humidity in 2500 m, relative humidity), vegetation, building and surface materials. Two, 24 hours simulation scenarios were run with the first scenario simulating the existing situation and the second scenario simulated the domain without vegetation.

To quantify human thermal comfort and discomfort, the ENVI-met results from the PMV for the

two scenarios were used. In particular, the PMV created by Fanger in the late 1960s is used worldwide as an outdoor comfort index and has previously been used in various urban and landscape studies [77,90-92]. It is also a function of the local climate and can reach values between −4 and +4 [93]. The PMV scale is defined between −4 (very cold that means extreme cold stress) and +4 (very hot that means extreme heat stress) where 0 is the thermal neutral (comfort) value [91,93].

*2.6. UFORE input data and methods*

The UFORE model was developed in the late 1990s by researchers at the United States Department of Agriculture (USDA) Forest Service, to quantify urban forest structure and its effects on function and values. The UFORE model components are relevant for this study as they quantify urban tree structure (e.g. LAI, leaf area, leaf biomass), hourly pollution removal by the urban forests and trees for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and particulate matter ($PM_{10}$), and hourly urban forest volatile organic compound (VOC) emissions and the relative impact of tree species on net ozone and carbon monoxide formation throughout the year. A more recent version of UFORE with a user-interface is known as i-Tree Eco. For a more complete description of the model, see [20,94].

Since users cannot directly access and run i-Tree Eco programming code, we used the actual UFORE model code (Version ACE 6.5 and U4D020701 with complete tree inventory option) to quantify air pollution removal during periods without precipitation, in which hourly dry deposition of CO, $NO_2$, $O_3$ and $PM_{10}$ is estimated with hourly meteorological and pollutant measurements, location information, and urban forest parameters [94]. In addition, we estimated annual VOCs emitted by trees in the streetscapes in order to assess the ecosystem disservices of these streetscapes by using UFORE (Version U4B020700). The hourly meteorological data for Bolzano, necessary to run the UFORE models, were obtained from the US National Oceanic Atmospheric Administration's National Climatic Data Center (NCDC) [95]. Hourly pollutant concentrations (CO, $NO_2$, $O_3$, $PM_{10}$) were obtained from the Laboratory of Physical Chemistry of the Autonomous Province of Bolzano that has three stations distributed within the city of Bolzano.

In June 2011, we used ArcGIS (Version 10) and a stratified random sample, according to land-cover classes, in order to obtain tree level data required by the UFORE models for the different streetscape types. During June and July 2011, trees were sampled and data recorded for each tree diameter at breast height (DBH). Other data collected were species, total tree height, height to live top, height to crown base, percent canopy missing, crown dieback, crown light exposure (CLE) [79,96]. These data were used in the UFORE model to estimate the ecosystem services of the treed streetscapes.

Since the aim of our research was to quantify tree-level air pollution removal using an existing tree inventory, the outputs of the UFORE model were specific to the measured 475 trees. The UFORE model estimated the average pollutants removed of CO, $NO_2$, $O_3$ and $PM_{10}$ for the measured trees according to tree DBH classes (see Table 2), regardless of species, and leaf-surface area of individual trees in Bolzano's inventory (I) using the formula:

$$I_x = R_t * (LA_x/LA_t) /N_x$$

where $_x$ is diameter class *x* (kg/tree) and $R_t$ is the total air pollution removed across all tree diameter size classes (kg). Also $LA_x$ is total leaf area in diameter size class *x* ($m^2$), $LA_t$ is the total leaf area of

all diameter size classes ($m^2$), and $N_x$ is the number of trees in diameter size class *x* [97]. Using this formula, we can for example assign the UFORE output as an average CO removal value of 4.70 g to every individual tree with a DBH of 20 cm in the Bolzano's tree inventory.

## 3. Results and discussions

### *3.1. Envi-met simulations*

The first simulation shows that during the summer (July) the potential temperature is slightly lower (<1 °C) in a treed piazza than in a tree lined street (Figure 1). This small difference is likely due to greater tree density and canopy cover in a piazza than in the street. The comparison between scenarios 1 and 2 shows a clear difference in potential temperatures (Figure 2). Thus, results have implications on the role of trees in reducing urban temperatures. For example, inner areas of the Piazza with vegetation (scenario 1) had lower temperatures (about 302 K = 28.85 °C) compared to scenario 2, areas of the piazza without vegetation and with hard landscape materials (temperature about 304 K = 30.85 °C). Overall, the higher temperature in scenario 2 is due to the fact, that hard landscape materials have lower albedos and higher heat capacities that absorb solar energy during the day [98].

The PMV values in this study (Figure 3) were not in the acceptable human thermal comfort range but scenario 1 has the highest amount of shade provided by trees consequently less solar irradiation. Therefore, scenario 1 is the most comfortable at 4:00 pm. In particular PMV is between 1.5 and 1.9 inside the piazza (scenario 1) that means a thermal perception of "warm" while scenario 2 has a PMV value inside the piazza >4.5 that means a thermal comfort perception of "very hot".

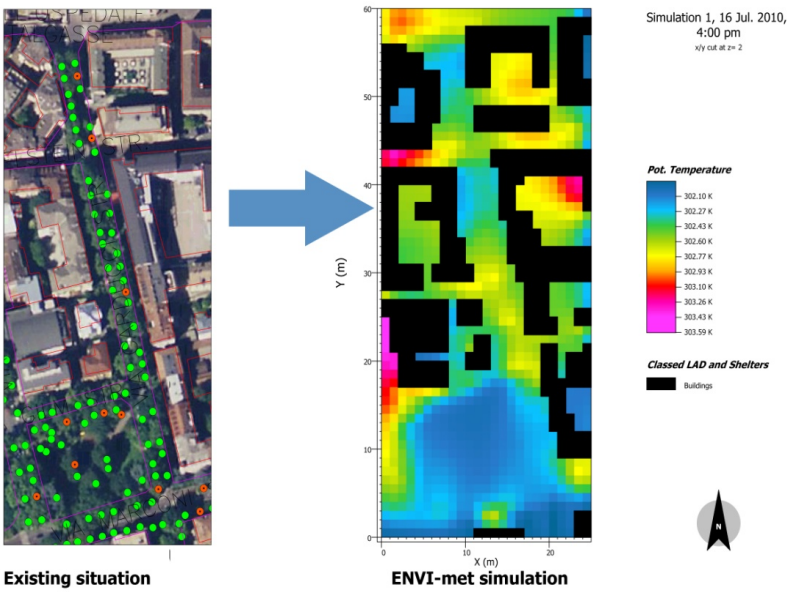


**Figure 1. ENVI-met simulation in Bolzano Italy: Potential temperature is lower in a piazza than in a street, dark blue colour represents low and red high temperatures.**

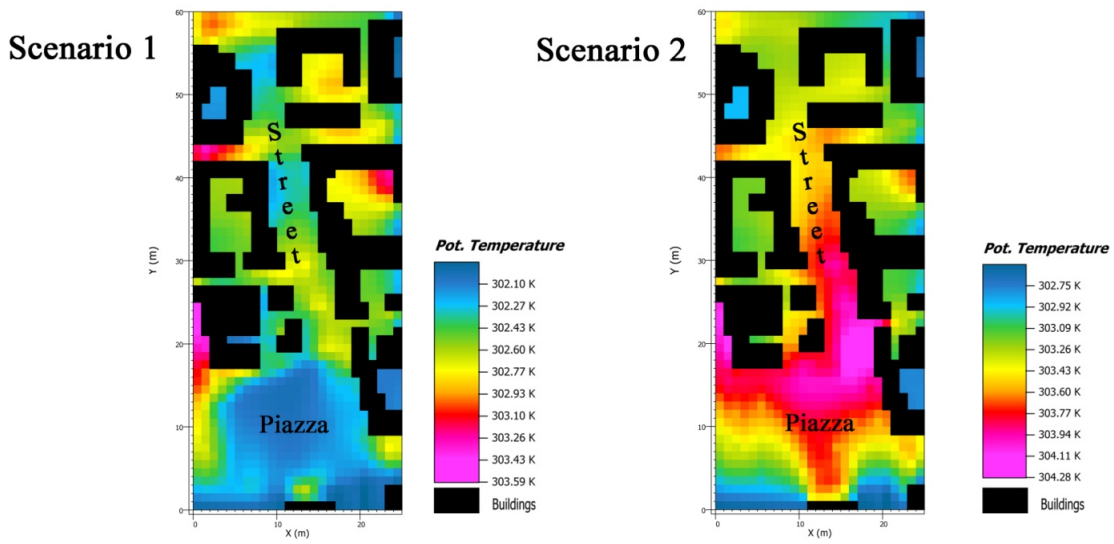


**Figure 2. ENVI-met: Potential temperature simulations at 2 m height at 04:00 pm in Bolzano, Italy. Scenario 1 accounts for vegetated streetscapes and scenario 2 assumes that vegetation is removed from the streetscapes.**

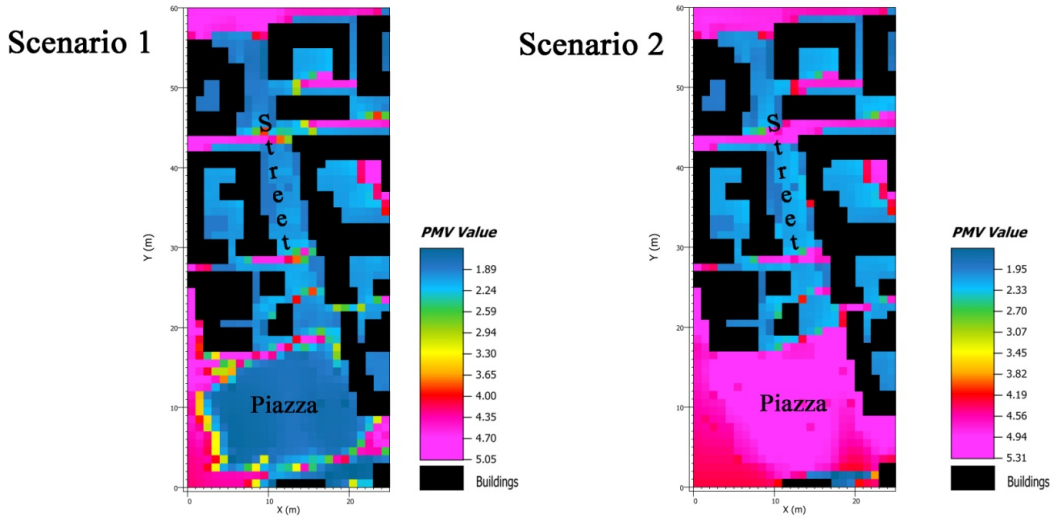


**Figure 3. Spatial distribution of predicted mean vote (PMV) biometeorological index at 4:00 pm. Scenario 1 accounts for vegetated streetscapes and scenario 2 assumes that vegetation is removed from the streetscapes.**

These results show that the ENVI-met model can be used to assess the outdoor thermal comfort of urban green infrastructure at the local-scale. Our PMV results are particularly useful for human bioclimatic maps, which have been used for planning purposes such as climate change impact analysis and urban heat island modification [77]. These findings are in accordance with other studies in which urban trees have effectively modified the microclimate and improved thermal comfort [92,99-103]. Taleghani et al. (2014) [51] for example, modelled a 5.8 degrees C temperature

difference between a heavily treed location and a nearby parking lot in Portland US using ENVI-met. Also, Ng et al. 2012 [101], conducted a study on the cooling effects of greening in Hong Kong using ENVI-met. They found that the amount of tree planting needed to lower pedestrians level air temperature by around 1 °C is approximately 33% of the urban area. Our PMV results in scenario 2 (Figure 3), corroborate Perini and Magliocco's findings in Italy, where an ENVI-met simulation without vegetation at street level revealed conditions conducive to human discomfort [103]. Thus, our approach can be used to compare urban design alternatives and have the potential to contribute to the planning of multifunctional green infrastructure [53].

### *3.2. UFORE analyses*

Total estimated air pollution removal by trees in Bolzano was 2.42 metric tons per year, with $O_3$ (1.2 t/yr) being the air pollutant that is removed the most and CO (0.03 t/yr) removed the least. Differences in removal rates per tree by diameter size classes (Table 2) are due to differences in the average amount of healthy leaf area per tree among the diameter size classes [97]. Total annual air pollution removal (kg/yr) was greatest for all pollutants in parks due to the greater number of trees (Figure 4). However, average annual air pollution removal (kg/yr) was greatest in the piazza due to the greater size of trees (Figure 5). Annual air pollutant removal per unit tree cover area ranged from 0.1 g/m$^2$ for CO to 4.2 g/m$^2$ for $O_3$. Total annual pollutant removal per unit tree cover area was 8.4 g/m$^2$ for all 4 pollutants. These values were lower than those estimated in Barcelona (9.35 g/m$^2$) at the urban forest scale [84] but this figure includes $SO_2$ which was not included in our estimates.

**Table 2. Average individual tree air pollution removal estimates (grams per year) for Bolzano according to tree diameter (DBH) size classes.**

| DBH Class (cm) | Carbon monoxide | Nitrogen dioxide | Ozone | Particulate matter <10 microns |
|---|---|---|---|---|
| 0.00–7.62 | 0.49 | 6.49 | 18.08 | 10.95 |
| 7.63–15.24 | 1.44 | 19 | 52.89 | 32.03 |
| 15.25–22.86 | 2.43 | 32.05 | 89.23 | 54.04 |
| 22.87–30.48 | 4.70 | 61.99 | 172.57 | 104.5 |
| 30.49–38.10 | 7.41 | 97.68 | 271.94 | 164.7 |
| 38.11–45.72 | 9.11 | 120.1 | 334.38 | 202.5 |
| 45.73–53.34 | 11.52 | 151.8 | 422.59 | 255.9 |
| 53.35–60.96 | 16.82 | 221.6 | 617.01 | 373.7 |
| 60.97–68.58 | 16.38 | 215.9 | 601.01 | 364 |
| 68.59–76.20 | 19.41 | 255.8 | 712.03 | 431.2 |
| 76.21–83.82 | 20.81 | 274.3 | 763.70 | 462.5 |
| 83.83–91.44 | 19.28 | 254.1 | 707.34 | 428.4 |
| 91.45–99.06 | 20.72 | 273.1 | 760.27 | 460.4 |
| 99.07–106.68 | 7.94 | 104.7 | 291.39 | 176.5 |
| 106.69–114.30 | 32.75 | 431.7 | 1201.84 | 727.8 |
| 114.31–121.92 | 16.68 | 219.9 | 612.13 | 370.7 |
| 121.93–129.54 | 32.97 | 434.6 | 1209.91 | 732.7 |
| Mean | 14.17 | 186.75 | 519.90 | 314. 85 |

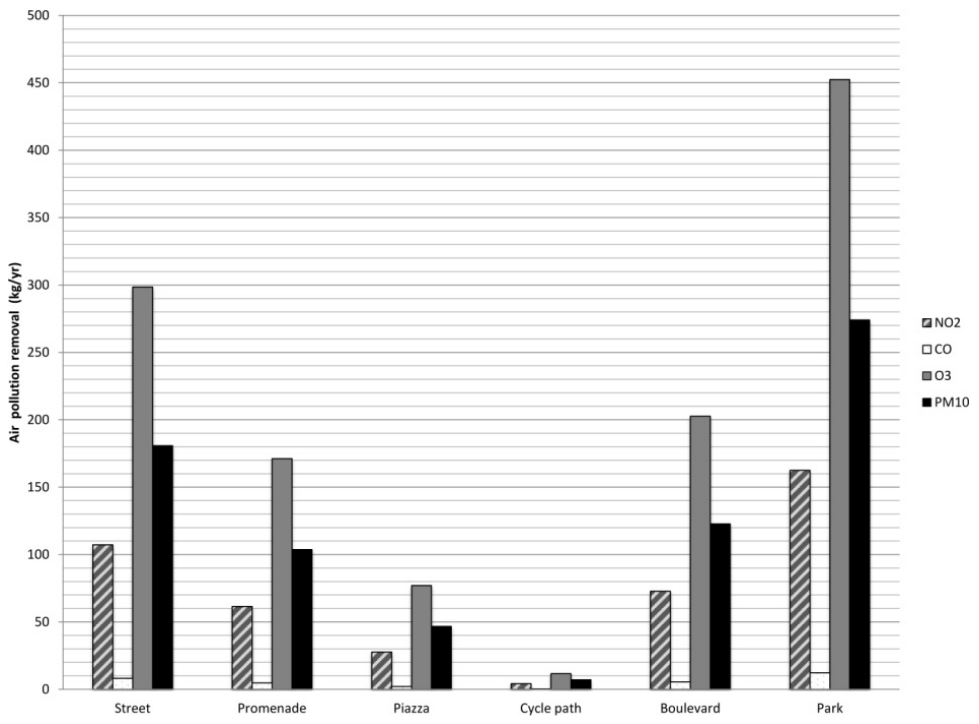


**Figure 4. Total annual air pollution removal of nitrogen dioxide, carbon monoxide, ozone, particulate matter less than 10 microns ($NO_2$, CO, $O_3$, $PM_{10}$, respectively) by different streetscape types in Bolzano, Italy.**

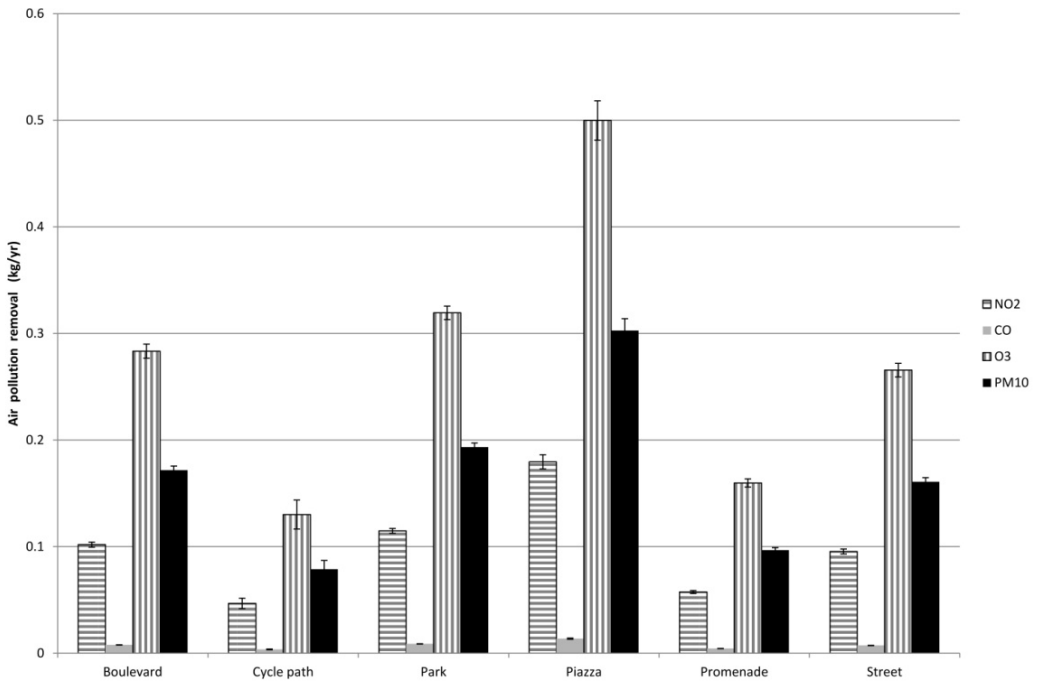


**Figure 5. Average annual air pollution removal of Nitrogen dioxide ($NO_2$), carbon monoxide (CO), ozone ($O_3$), particulate matter ($PM_{10}$) by different streetscape types in Bolzano, Italy. Error bars represent ± one standard error of the mean.**

But, our results were higher than other UFORE's case studies in Italian cities [54,55,104]. In particular, our estimates of $PM_{10}$ was 314.85 g/tree versus 196 g/tree in Milan and 198 g/tree in Florence, and 150 g/tree (tree >20 m) in Forlì. Our estimates of $O_3$ (519.90 g/tree) was also much higher than estimates in Milan with 68 g/tree [54], in Florence with 170 g/tree [55], and in Forlì with 100 g/tree (tree >20 m) [104]. A more detailed interpretation of these studies can explain these disparate results. We found that higher air pollution removal in Bolzano not only depends on climate and pollution, but structural characteristics such as the amount of healthy leaf-surface area and DBH distribution of the modelled tree population. Specifically, if we compare the average tree DBH in Milan (39.6 cm) and its pollution removal with that of Bolzano's 38.11–45.72 cm DBH class pollution removal rate, we found a $PM_{10}$ value of 202.5 g/tree in Bolzano; a removal rate much more similar to the 196 g/tree found in Milan.

As such, air pollution removal differences among cities depend on several other factors as well such as ambient air pollution concentration, in-leaf season period, percent of evergreen leaf area, amount of precipitation and other meteorological variables [20]. Therefore, the size, growth form and health condition of individual plants could affect the amount of pollutant removal per tree [105]. The UFORE model has a number of assumptions [106], for example, it does not take into account occult or wet deposition and therefore is likely to underestimate the total air pollutant deposition [106].

We also used the UFORE model to account for an ecosystem disservice by estimating total VOC emissions and found 5.61 mg C/m$^2$/hour in Bolzano, which might contribute to ozone formation [55,107]. The emission of these organic compounds varied throughout the year and the day [97] with the highest emission was in August and at 2 pm. The tree genera in Bolzano with the highest VOCs emissions were *Cedrus* (0.36 kg of isoprene, 29.0 kg of monoterpene, 31.7 kg of other VOCs) and *Platanus* (35.5 kg of isoprene, 0.24 kg of monoterpene, 4.17 kg of other VOCs). At the species level, emissions of BVOC in Bolzano were lowest for *Pyrus* species and *Olea europaea* L. Therefore to reduce $O_3$ levels in Bolzano, managers should change species composition using low VOC-emitting species. Furthermore, in planning large scale tree planting programs, landscape manager should take into account the potential for BVOC emissions when considering how to reduce emission of $O_3$ precursors [108].

### *3.3. Limitations*

A number of limitations of the present study should be acknowledged. The ENVI-met model version 3.1 Beta 5 used in our modelling does not incorporate the forcing of weather variables after initialisation [109] and thus all buildings in our model simulations were assumed to have the same albedo value. Also, The UFORE/ i-Tree Eco model has several limitations that should be taken into account when analyzing its outcomes [78]. Model uncertainty includes non-homogeneity in spatial distribution of air pollutants, site-specific particle re-suspension rates, transpiration rates, or soil moisture status [78,110]. The i-Tree Eco model has recently provided a good estimation of $O_3$ flux when compared to measured flux by eddy covariance estimates in Italy. However, some overestimations were observed in estimated values especially in hot dry periods [111].

Treed streetscapes have been determined to mitigate urban temperatures and air pollution concentrations, but we admit that there are many other ecosystem services that were not considered in this study such as, e.g. cultural services (historical, aesthetic, educational, and recreational). Since the sustainability of cities is increasingly being studied in applied landscape and urban ecology [48],

urban planners and designers need to determine and communicate the relative value or importance of these ecosystem services at the appropriate scale to key stakeholders and the community. Indeed future research incorporating the effects of climate change on local-scale green infrastructure ecosystem functions is warranted. Such approaches can use cost-benefit analyses for example to ensure that disservices and costs do not outweigh the services and benefits provided by urban green options [112]. Therefore, further research is needed to quantify other ecosystem disservices and costs such as pollen allergy, $CO_2$ emissions due to urban forest management, and maintenance and management cost.

## 4. Conclusions

Our literature review documents several studies of how urban treed streetscapes and green infrastructure provide many environmental, social, recreation and beautification benefits to society. But recent studies such as those of Maher et al. (2013) [46] who found a 50% reduction in particulate matter levels inside houses screened by street trees, and Escobedo et al. (2011) [19] emphasize the need to account for scale when assessing urban ecosystem service provision. Thus, our findings contribute to this need for local-scale information. Further, most existing studies are from North American cities, and have been conducted at the city-wide scale; as such, ours is one of the few studies on the effects of treed streetscape on air pollution removal, ambient temperature regulation at the local-scale in a European city. This study used a framework of field, pollution, and meteorological data and integrated simulation models to quantify the role of urban greening in improving environmental quality in an Italian city. Models results can be used to provide information on air pollution removal at the tree and streetscape scale, temperature mitigation by different streetscape types. In addition, it explored the effect of VOC emission or ecosystem disservices associated with streetscapes at the tree and species level.

Our approach and results can also be used in the assessment of the ecosystem services of urban ecosystems and green infrastructure as required by the EU Biodiversity strategy. Specific findings can be used to better design and plan for urban streetscapes, improved environmental quality and mitigation of the urban island effect. In order to protect human health and the environment, Bolzano's city manager should take into account our findings and incorporate this information into their air quality plan for $NO_2$ reduction. As our study shows, improving Bolzano's green infrastructure can contribute to reduce the local-scale level of air pollutants. Incorporating finding into models, can possibly be used in flow diagrams [113], so that planners can investigate and quantify the visible benefits of planting trees to reduce pollutant concentrations and improving thermal comfort while providing aesthetic benefits.

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## Conflict of interest

The authors declare no conflict of interest.

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