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Air quality impact of an urban park over time

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Abstract

The Urban Forest Effects (UFORE) model, a computer model designed to use tree allometric, air pollution and meteorological data to statistically estimate urban forest characteristics and various urban forest functions, was applied to the main park in the city of Florence, Italy (Cascine Park), in 1985 and 2004, in order to study how the natural and man-made evolution of the park affected its ability to control air quality. Plant data were for both the years, while climate and pollutant data were for year 2004 only, in order to remove the variability due to changes in the atmospheric variables. The results show that the forest growth compensated the losses due to cuttings and damages by extreme climatic events, so that the overall amount of pollutants removed from the air did not change from 1985 to 2004 (72.4-69.0 kg/ha). In contrast, the amount of carbon storing and biogenic volatile organic compound emission decreased over time, because of a reduction in the number of large trees and of isoprene-emitting individuals, but the results were very variable plot by plot. The species were ranked according to their ability of controlling air quality. These data can be used as a decision tool for establishing cuttings and new plantings in urban planning and their effects on air quality under Mediterranean climate conditions.

Keywords: Urban forests, air pollution, UFORE, Mediterranean climate, Firenze, VOC

1. Introduction

Urbanization is a spreading phenomenon in almost all the world [1,2]. Urban environments are often characterized by higher mean temperatures, concentrations of greenhouse gases and atmospheric pollutants compared with surrounding rural areas [2]. In contrast, ozone (O_3) concentrations are typically higher in suburban and rural areas than in the cities, due to the nature of O_3 formation process [3], although the thresholds for protection of people and vegetation may be exceeded in urban air too [4].

The role of urban vegetation in controlling air pollution is considered one of the major benefits that urban green can provide [5]. Urban forests are of topical importance as deposition of gaseous pollutants is typically greater in woodlands than in shorter vegetation [6]. Dry deposition (including stomatal uptake and non-stomatal deposition upon plant surfaces) is a major mechanism by which plants remove pollutants from the air [7]. In contrast, emission

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of biogenic volatile organic compounds (BVOCs) can contribute to O_3 and aerosol formation [8]. Although the amount of BVOCs in major urban areas is often negligible when compared to anthropogenic sources, they are 2–3 times more reactive than a weighted average of hydrocarbons from gasoline combustion [9], thus increasing their contribution to pollutant formation. BVOCs include the isoprenoids (isoprene and monoterpenes as well as sesquiterpenes and homoterpenes) and minor compounds such as alkanes, alkenes, carbonyls, alcohols, esters, ethers, and acids. Isoprenoids protect plant membranes against oxidative stressors, including O_3 [10]. Tree and shrub species have been classified on the base of hourly emission rates of isoprene and monoterpene, thus identifying low O_3-forming potential species [11,12].

The Urban Forest Effects (UFORE) model is a computer model designed to use tree allometric, air pollution and meteorological data to statistically estimate urban forest characteristics and various urban forest functions [13,14]. UFORE has been used all over the world [e.g. 15,16,17,18] including a few studies in Mediterranean-type climate (Fuenlabrada, Spain [19]; Santiago, Chile [20]; Porta Venezia gardens in Milan, Italy [21]; a tramway under construction in Florence, Italy [3]) where O_3 levels are of most concern. Ozone pollution, in fact, is pronounced in regions with strong photochemical activity, such as Mediterranean-type climates [22].

The aim of this study was to study how the natural and man-made evolution of an urban park in the city of Florence, Italy, affected the forest ability to control air quality. Two years were compared (1985 and 2004) by applying the UFORE model.

2. Materials and methods

Florence (43°47'N, 11°15'E; 50 m a.s.l.) is a city of central Italy, with around 350,000 inhabitants over 102 km^2. Cascine park is the largest green area in Florence and covers 118 ha, out of which 39 ha are a semi-natural forest. The park is 2 km far from the city centre. The climate is classified between the Mediterranean and the humid subtropical climates [23], with 912 mm as average annual precipitation and 14.7°C as annual mean temperature. The soil is alluvial sediments. The management is carried out by the Florence municipality with the main aim of maintaining a natural structure and safety for customers.

Table 1. 24-h average of hourly concentrations of carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2) particulate matter with diameter lower than 10 µm (PM_{10}) and sulphur dioxide (SO_2) in the year 2004. Monitoring stations are referred to by different letters.

Pollutant	Station	Average
CO [ppm]	a,b,c,d,e,f	0.403
O_3 [ppb]	a,e,f,g	23.2
NO_2 [ppb]	a,b,c,d,e,f, g	22.5
PM_{10} [µg/m^3]	a,b,c,d	34.6
SO_2 [ppb]	c,d,h	1.2

[a]Boboli, [b]Viale Gramsci, [c]via Bassi, [d]via delle Mosse, [e]via di Novoli, [f]via di Scandicci, [g]Settignano, [h]Scandicci.

The plant data (plant species, diameter at breast height, total tree height, height to base of live crown, crown width, percent canopy missing, crown dieback percent, crown light exposure) were obtained from two full-tree inventories that were carried out in 1985 [24] and 2004 [25] by applying the same survey methodology in eight plots i.e. over 5.5 ha. The meteorological data for Florence were obtained from the WMO database [www.climateprogress.org]. The pollution data were obtained from the local air quality network [www.arpat.toscana.it/aria/], that includes eight stations distributed all over the Florence city area (but not in the Cascine park). Averages are summarized in Table 1. As air quality monitoring in Florence started in 1992, only data for 2004 were used, which allowed us to remove the variability due to changes in the atmospheric variables over time. The modules B, C and D of UFORE were run by the iTree software (v3.0). The following variables were calculated per each tree and year: ground cover; leaf surface and biomass; carbon storage i.e. the total carbon stored into a tree; carbon sequestration i.e. the annual carbon uptake; removal of carbon monoxide (CO), O_3, nitrogen dioxide (NO_2), particulate matter with diameter lower than 10 µm (PM_{10}) and sulphur dioxide (SO_2); emission of isoprene, monoterpenes and other BVOCs.

Comparisons between the two years were carried out by applying a t-test with 0.05 as level of significance. Differences between species were tested by unequal-N Tukey post-hoc and Kruskal-Wallis non-parametric multiple comparison tests for normal and not-normal distribution variables, respectively. Normality was checked by Kolmogorov–Smirnov D test ($p<0.05$). Only species with more than 10 individuals were included in this test.

3. Results

Over time, the forest showed a significant growth in mean diameter (+19%), leaf surface (+74%) and leaf biomass (+64%) (Table 2). The mean tree height, in contrast, showed a tendency to decrease (-12%, p=0.082) because of wind throws of the highest trees due to a severe wind storm in 2003. The mean number of trees also showed a tendency to decrease (-37%, p=0.062) because of cuttings and damages by drought and the wind storm. The total number of trees in the eight plots decreased from 1396 to 885. The increase in ground cover (+13%) was not significant because of elevated variability between plots.

Table 2. Average (standard error in parenthesis) of the structural variables in 1985 and 2004. The level of significance p shows the significance of the differences between the two years (t-test, N=8 plots).

Variable	1985	2004	p
Diameter at breast height (cm/tree)	27.22 (0.62)	32.31 (1.23)	0.003
Height (m/tree)	14.89 (0.82)	13.10 (0.49)	0.082
Ground cover (m²/tree)	13.31 (0.74)	15.02 (1.10)	0.216
Leaf surface (m²/tree)	53.85 (4.31)	93.66 (11.40)	0.006
Leaf biomass (kg/tree)	3.45 (0.27)	5.67 (0.68)	0.009
Number of trees	174.50 (25.78)	110.63 (18.07)	0.062

The average carbon storage per tree was similar in 1985 and 2004, but the reduction in the number of trees over time implied a 43% decrease in the carbon store of the whole forest (Table 2). Also the annual carbon sequestration per tree was similar in the two years, with a 34% decrease in the total amount sequestered in 2004 relative to 1985. Although the removal of pollutants per tree increased over time, the total amounts slightly decreased, still because of the reduction in the number of trees, so that the total amount of pollutants removed from the air in the eight plots showed just a small 5% reduction from 1985 to 2004. Shifts in the species composition implied similar isoprene and monoterpene emission per tree in the two years, and a 53% and 10% reduction in the total emission of isoprene and monoterpenes, respectively, in 2004 relative to 1985. In particular, the wind storm of 2003 caused throws of many trees of *Quercus robur* and *Populus alba*, that are highly emitting species. In contrast, the reduction of the number of trees compensated the increase in the average emission of other BVOC per tree, so that the total emission of other BVOC was just 2% lower in 2004 than in 1985. All these changes in BVOC emission resulted in a not significant variation per tree and in a 38% reduction of the total emissions from 1985 to 2004.

The most effective species in carbon uptake and sequestration were *Populus alba* and *Quercus robur* (Table 4). *Pinus pinea*, *Aesculus hippocastanum* and *Populus alba* were the most effective species in removing CO, O_3, NO_2 and SO_2 from the air, while *A. hippocastanum* was the most effective as filter for PM_{10}. Therefore, *P. pinea*, *A. hippocastanum* and P. *alba* were the best species for the removal of total pollutants. However, *P. alba* was a strong emitter of isoprene, followed by *Quercus robur* and *Q. ilex*. *Pinus pinea* was a strong emitter of monoterpenes, followed by *A. hippocastanum* and *Gingko biloba*. *P. pinea*, *A. hippocastanum, P. alba* and *Ligustrum lucidum* emitted elevated amounts of other BVOC. The species emitting negligible amounts of isoprene were *L. lucidum, G. biloba, C. betulus* and *Tilia* species. *L. lucidum* and *Tilia* also emitted very low amounts of monoterpenes. Therefore, the species that showed a high potential of ozone formation were *P. pinea, A. hippocastanum*, *Q. robur*, *G. biloba, Q. ilex*, and mainly *P. alba*, while *Fraxinus ornus* and *Carpinus betulus* showed the lowest emission of total BVOCs.

Table 3. Average (standard error in parenthesis) and total amount of the functional variables in 1985 and 2004. The level of significance p shows the significance of the differences between the two years (t-test, N=8 plots).

Variable	Average 1985	Average 2004	p	Total 1985	Total 2004
Carbon storage (kg)	370.8 (25.5)	354.6 (22.4)	0.640	532,007	303,173
Carbon sequestration (kg/year)	9.10 (0.30)	9.79 (0.45)	0.221	12,726	8,346
CO removal (g)	0.03 (<0.01)	0.05 (0.01)	0.009	41.5	40.6
O_3 removal (g)	73.6 (5.7)	121.0 (14.4)	0.009	99,225	96,968
NO_2 removal (g)	47.8 (3.7)	78.6 (9.4)	0.009	64,493	63,027
PM_{10} removal (g)	164.6 (11.6)	256.5 (28.1)	0.009	223,838	208,767
SO_2 removal (g)	8.03 (0.63)	13.21 (1.57)	0.009	10,837	10,590
Total removal of pollutants (g)	294.0 (21.6)	469.4 (53.3)	0.009	398,435	379,393
Isoprene emission (g)	41.4 (6.1)	32.5 (6.2)	0.323	58,374	27,200
Monoterpene emission (g)	3.41 (0.42)	5.20 (0.96)	0.109	4,381	3,939
Emission of other VOC (g)	16.3 (1.3)	26.8 (3.2)	0.009	22,023	21,506
Total VOC emission (g)	61.2 (7.1)	64.5 (7.3)	0.746	84,779	52,646

4. Discussion and conclusions

Pollution removal varies among cities depending on the amount of tree cover (increased tree cover leading to greater total removal), pollution concentration (increased concentration leading to greater downward flux and total removal), length of the in-leaf season (increased growing season length leading to greater total removal), amount of precipitation (increased precipitation leading to reduced total removal via dry deposition), and other meteorological variables that affect tree transpiration and deposition velocities (factors leading to increased deposition velocities would lead to greater downward flux and total removal) [16]. In the Cascine park of Florence, the forest growth in 20 years compensated the losses due to cuttings and damages by extreme climatic events, so that the overall amount of pollutants removed from the air did not change from 1985 to 2004 (72.4-69.0 kg/ha). In contrast, the amount of carbon storage and biogenic volatile organic compound emission decreased over time (-43% and -38%, respectively), because of a reduction in the number of trees and of isoprene-emitting individuals, but the results were very variable plot by plot. However, the carbon storage was still very high in 2004, being 55.1 t/ha. In the USA, urban forests have been estimated to store 25.1 t/ha of carbon, while extra-urban forests store 53.5 t/ha [26]. Among the pollutants here investigated, the highest removal was for PM_{10}, followed by O_3, NO_2, SO_2 and finally CO. In the US, urban forests were estimated to remove about 711,000 metric ton ($3.8 billion value) of air pollution per year, and the amount of pollution removed was typically greatest for O_3, followed by PM_{10}, NO_2, SO_2 and CO [16]..

Table 4. Average of plant carbon storage (C in kg) and sequestration (CS in kg/year), removal of CO, O_3, NO_2, PM_{10}, SO_2 and total removal (Total, in g), emission of isoprene (IS), monoterpenes (MT), other volatile organic compounds (OVOC) and total VOC (TVOC) in g, for the species with more than 10 individuals. Different letters show significant differences among species in each column ($p<0.05$).

Species	**C**	**CS**	**CO**	**O_3**	**NO_2**	**PM_{10}**	**SO_2**	**Total**	**IS**	**MT**	**OVOC**	**TVOC**
Acer campestre L.	47.2 cd	1.77 cd	<0.001 bcd	4.8 bd	3.14 bcd	12.5 bc	0.53 cd	21.0 bcd	0.012 bc	0.977 ad	1.07 cd	2.06 bcde
Acer pseudoplatanus L.	69.3 cd	2.85 cd	0.010 abcd	28.1 abcd	18.3 abcd	62.1 abc	3.07 abcd	112 abcd	0.073 abc	5.686 ad	6.22 abcd	12.0 abcde
Acer sp.	7.2 abcd	0.29 abcd	<0.001 abcd	1.8 abcd	1.15 abcd	4.21 abcd	0.19 abcd	7.32 abcd	<0.001 abc	0.360 abcd	0.39 abcd	0.75 abcde
Aesculus hippocastanum L.	149 abcd	4.15 abcd	0.040 a	97.7 a	63.5 a	182 a	10.7 ac	354 a	0.252 ab	19.77 a	21.61 a	41.6 ab
Broussonetia papyrifera (L.)Vent	39.8 bcd	2.14 bcd	0.010 abcd	21.9 abcd	14.2 abcd	65.7 abc	2.39 abcd	104 abcd	6.510 abc	0.557 abcd	4.85 abcd	11.9 abcde
Carpinus betulus L.	5.8 abcd	0.7 abcd	<0.001 bcd	1.1 bcd	0.69 bcd	2.62 bd	0.11 bcd	4.49 de	<0.001 abc	0.213 abcd	0.23 bcd	0.45 bcde
Celtis australis L.	12.1 cd	0.49 cd	0.003 abcd	12.8 ac	8.34 ac	27.6 ad	1.40 ab	50.1 ae	0.034 ab	0.325 ad	2.84 a	3.19 abcd
Fraxinus angustifolia Vahl.	18.7 d	1.36 d	0.002 bcd	8.9 bd	5.77 bcd	17.0 bcd	0.97 bcd	32.6 bcd	0.023 bc	0.111 cd	1.96 cd	2.10 cde
Fraxinus ornus L.	9.5 d	0.65 d	<0.001 d	2.8 d	1.84 d	4.99 cd	0.31 d	9.98 d	0.006 c	0.036 cd	0.63 d	0.67 e
Ginkgo biloba L.	231 abcd	8.31 abcd	0.020 bcd	44.8 abcd	29.1 abcd	147 ab	4.89 abcd	226 abcd	<0.001 bc	17.00 abc	9.91 bcd	26.9 bcde
Laurus nobilis L.	50.8 cd	2.64 cd	0.004 d	10.9 d	7.09 d	21.2 bc	1.19 abcd	40.4 cd	0.030 bc	0.153 ce	2.65 cd	2.83 de
Ligustrum lucidum Ait.	27.4 d	2.42 d	0.020 abcd	50.1 abcd	32.6 abcd	80.6 abc	5.48 abcd	169 abcd	<0.001 ab	<0.001 c	12.16 abcd	12.2 bcde
Pinus pinea L.	333 abcd	6.63 bcd	0.050 ab	112 ab	73.0 ab	164 abc	12.3 ab	362 abc	0.294 ab	46.72 ab	27.25 ab	74.3 a
Populus alba L.	792 ab	14.2 ab	0.030 ab	78.5 ab	51.0 ab	128 ab	8.57 ab	266 ab	142 a	0.992 cd	17.37 ab	16.4 ab
Prunus laurocerasus L.	5.7 cd	1.1 cd	0.003 bcd	7.9 bcd	5.15 bcd	19.7 bc	0.87 bcd	33.6 be	0.020 abc	0.110 cd	1.92 bcd	2.05 bcde
Quercus ilex L.	50.9 abc	1.64 abc	0.003 abc	11.6 abcd	7.53 abcd	19.9 bd	1.27 abcd	40.2 abcd	20.95 a	0.292 bcd	2.56 abcd	23.8 a
Quercus robur L.	353 a	5.02 a	0.009 ab	18.8 ab	12.2 ab	37.8 ab	2.05 abcd	70.9 ab	33.99 a	0.474 abcd	4.16 abcd	38.6 a
Robinia pseudacacia L.	31.8 bcd	1.50 bcd	<0.001 d	4.5 d	2.91 d	12.4 bc	0.49 d	20.3 bcd	8.10 a	0.114 cd	0.99 d	9.21 abc
Tilia sp.	19.5 bcd	0.58 bcd	0.003 ac	11.4 ac	7.41 ac	31.0 ad	1.25 ab	51.1 ae	<0.001 c	<0.001 cd	2.52 ab	2.52 bcde
Ulmus sp.	8.8 bcd	0.35 bcd	0.002 abc	7.5 ac	4.87 ac	14.7 ad	0.82 ab	27.9 ae	0.021 ab	0.096 de	1.66 ab	1.77 bcde

The species of the Cascine park were ranked according to their ability of controlling air quality. While *A. hippocastanum, P. alba* and *P. pinea* were the best species for the removal of total pollutants, they showed a high potential of ozone formation, being among the strongest emitters of BVOCs. Species with intermediate ability of pollution removal and low ozone-forming potential, such as *Tilia* sp. and *Celtis australis*, may be more suitable for urban planning in Mediterranean environments. A weakness of UFORE is that the parameterisation of Mediterranean species is not appropriate. In fact, *Quercus ilex*, a Mediterranean evergreen tree, resulted to be a major emitter of isoprene, while it is known to emit monoterpenes [8].

In conclusion, the management of the Cascine park forest over 20 years maintained an optimal efficiency of pollution removal and reduced the emission of ozone-forming organic compounds. Assuming that the results may be extended from our eight plots to the whole forested area, the Cascine park would at present remove 2.69 t/yr of pollutants from the air of Florence and emit 373 kg/yr of biogenic volatile organic compounds.

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