Urban forests near roads do not reduce gaseous air pollutant concentrations but have an impact on particles levels

Vesa YLI-PELKONEN[1*], Heikki SETÄLÄ[2], Viljami VIIPPOLA[2]

[1]University of Helsinki, Department of Environmental Sciences, P.O. Box 65, FI-00014, University of Helsinki, Finland; vesa.yli-pelkonen@helsinki.fi

[2]University of Helsinki, Department of Environmental Sciences, Niemenkatu 73, FI-15140, Lahti, Finland; heikki.setala@helsinki.fi, viljami.viippola@helsinki.fi

*Corresponding author
Vesa Yli-Pelkonen
Department of Environmental Sciences, P.O. Box 65, FI-00014, University of Helsinki, Finland.
Phone: +358 50 586 9166; e-mail: vesa.yli-pelkonen@helsinki.fi

Abstract

The ability of urban vegetation to improve air quality for the benefit of urban residents is often considered fact since plants can absorb and capture air pollutants. However, there is little empirical evidence that urban air quality at the local scale is improved by the presence of, e.g. trees, especially in northern climatic regions. We studied the impact of urban forest vegetation on the levels of five types of air pollutants (NO_2, ground-level O_3, anthropogenic and biogenic VOCs, and particulate matter) in near-road environments during summer (June) using passive samplers in Helsinki, Finland. Concentrations of gaseous pollutants did not differ significantly between tree-covered and adjacent open areas, while particle pollutant levels were significantly lower in tree-covered areas than in adjacent open, treeless areas. Vegetation-related variables (canopy closure, tree number and size, and ground vegetation) did not explain differences in air quality. Our results suggest that the role of urban, mostly deciduous, vegetation is negligible in improving local air quality, in terms of the anthropogenic pollutants measured here, in northern climates. However, air particulate pollution, which is likely to be dominated by large-sized particles in our study, can be reduced by urban vegetation.

Highlights:

- Gaseous pollutant concentrations did not differ between tree-covered and open areas
- Particle pollutant levels were significantly lower in tree-covered areas
- Vegetation-related variables did not explain the difference in particulate levels

1. Introduction

Poor air quality due to air pollutants is amongst the most recognized environmental problems in urbanized areas around the world. In Europe, the levels of air pollutants have generally decreased within the past decades, but in many urban areas the levels of particulate matter, nitrogen dioxide (NO_2), ground-level ozone (O_3), and anthropogenic volatile organic compounds (AVOC) are still high enough to cause severe risk to human health (EEA, 2014). Most of these air pollutants originate from energy production and road traffic (EEA, 2014).

Although reducing air pollutant emissions is likely to be the most effective way to improve air quality (EEA, 2014), it is widely believed that vegetation – due to its ability to absorb and capture air pollutants with its large leaf area – can be used to mitigate urban air pollution problems (Beckett, Freer-Smith & Taylor, 2000a; Nowak, 2006; Nowak, Crane & Stevens, 2006). For example, trees and herbaceous plants capture particulate pollution by dry deposition on their large leaf surfaces (Hofman, Stokkaer, Snauwaert & Samson, 2013; Räsänen, Holopainen, Joutsensaari, Ndam, Pasanen, Rinnan & Kivimäenpää, 2013; Weber, Kowarik & Säumel, 2014).

Furthermore, trees and other vegetation can absorb gaseous air pollutants, mainly from air to leaf, where gases such as NO_2 (Chaparro-Suarez, Meixner & Kesselmeier, 2011; Rondón & Granat, 1994; Takahashi, Higaki, Nohno, Kamada, Okamura, Matsui, Kitani & Morikawa, 2005), O_3 (Harris & Manning, 2010; Manes, Incerti, Salvatori, Vitale, Ricotta & Costanza, 2012; Wang, Zhou, Wang, Gao, Zheng, Tong & Ouyang, 2012) and anthropogenic volatile organic

compounds (AVOC) (Doty, James, Moore, Vajzovic, Singleton, Ma, Khan, Xin, Kang, Park, Meilan, Strauss, Wilkerson, Farin & Strand, 2007; Keymeulen, Schamp & Van Langenhove, 1995) are absorbed through the stomata into the leaf interior. Consequently, the mitigation of air pollution is often considered an important ecosystem service provided by urban vegetation (e.g. Chaparro & Terradas, 2009; Jim & Chen, 2008; Manes et al., 2012; Nowak, Crane, Stevens, Hoehn, Walton & Bond, 2008).

Forests and other vegetation in rural and urban areas emit biogenic volatile organic compounds (BVOC) while human activities produce AVOCs, which, together with NO_x ($NO + NO_2$), play a key role in the formation of ozone (O_3) in the tropospheric air (Calfapietra, Fares, Manes, Morani, Sgrigna & Loreto, 2013; Loreto & Schnitzler, 2010). Under VOC-limited conditions, ground-level O_3 levels are usually lower in urban (high NO_x levels) than in rural areas with NO_x-limited conditions (low NO_x levels, but higher BVOC levels) (Calfapietra et al., 2013; EEA, 2014). However, in recent years, O_3 levels in European and North American cities have increased more than in rural sites, although peak values are decreasing in both environments (Paoletti, De Marco, Beddows, Harrison & Manning, 2014).

Despite the wealth of studies suggesting that urban vegetation is able to purify air for the benefit of urban inhabitants, contradictory results and comments have emerged recently (Gromke & Ruck, 2009; Harris & Manning, 2010; Pataki, Carreiro, Cherrier, Grulke, Jennings, Pincetl, Pouyat, Whitlow & Zipperer, 2011; Pataki, Alberti, Cadenasso, Felson, McDonnell, Pincetl, Pouyat, Setälä & Whitlow, 2013; Vos, Maiheu, Vankerkom & Janssen, 2013). Critique is based on the interpretation of model studies, according to which ambient air quality should uniformly

93 be improved by the presence of vegetation in the urban environment, where pollutant
94 concentrations are high (e.g. Baumgardner, Varela, Escobedo, Chacalo & Ochoa, 2012;
95 Hirabayashi, Kroll & Nowak, 2012; McDonald, Bealey, Fowler, Dragosits, Skiba, Smith,
96 Donovan, Brett, Hewitt & Nemitz, 2007; Morani, Nowak, Hirabayahsi & Calfapietra, 2011;
97 Nowak, Hirabayashi, Bodine & Hoehn, 2013).
98
99 Only a few studies exist in which pollutant levels have been measured locally, e.g. within a
100 forest or park canopy and compared to pollution levels in adjacent open areas (see Brantley,
101 Hagler, Deshmukh & Baldauf, 2014; Cavanagh, Zawar-Reza & Wilson, 2009; Freer-Smith,
102 Beckett & Taylor, 2005; Harris & Manning, 2010; Setälä, Viippola, Rantalainen, Pennanen &
103 Yli-Pelkonen, 2013; Streiling & Matzarakis, 2003; Viippola, Rantalainen, Yli-Pelkonen, Tervo
104 & Setälä, 2016; Yin, Shen, Zhou, Zou, Che & Wang, 2011). As such, to enhance our
105 understanding on the uptake, deposition, and re-suspension rates of pollutants by urban
106 vegetation, more on-site, small-scale measuring campaigns are needed (Pataki et al., 2011, 2013;
107 Whitlow, 2009).
108
109 Our main objective is to explore the ability of urban vegetation to purify gaseous and particulate
110 air pollutants of anthropogenic, mostly traffic-derived origin under northern summertime
111 conditions in the near-road environment in Finland. This study builds on the same empirical
112 principles as applied by Setälä et al. (2013), in which air pollutant levels (concentrations of NO_2
113 and VOCs and mass deposition of particles) were measured in open and tree-covered areas in
114 late summer and winter using passive samplers in urban near-road environments in two cities
115 (Helsinki and Lahti) in Finland. The present study was conducted during midsummer (mainly

June) when the total leaf-area and gas exchange between leaves and the ambient air is expected to be higher than in Setälä et al. (2013). The sampling protocol of the present study was also slightly different by fine tuning the position of the sampling sites in relation to the prevailing wind direction. Based on previous findings in similar environments (Setälä et al., 2013) we hypothesized that concentrations of gaseous air pollutants should not differ between urban tree-covered and open, treeless areas in near-road environments, while air particulate levels (mass of all deposited particles) should be lower in such tree-covered areas. We also assumed that the removal of pollutants, particularly air particulates, should relate to the volume and structure of vegetation in the tree-covered areas.

2. Methods

2.1. Sampling methods

We measured air pollutant levels using dry deposition passive samplers, placed either under tree canopies in tree-covered areas or in adjacent treeless open areas in near-road environments in the Helsinki Metropolitan Area (60°10′15″N, 24°56′15″E), southern Finland (Fig. 1). The air pollutants measured were i) nitrogen dioxide (NO_2), ii) ground-level ozone (O_3), iii) a selection of typical anthropogenic volatile organic compounds (AVOCs), iv) biogenic volatile organic compounds (BVOCs), which is a selection of the most common monoterpenes in Finnish forests alongside isoprenes (Lindfors & Laurila, 2000), and v) particulate matter. For NO_2 and O_3 we used diffusive samplers developed by the Swedish Environmental Research Institute IVL, where the gas is adsorbed to a filter paper inside the collector and the amount of gas is analyzed by

extracting it from the filter to distilled water, after which the amount of gas is determined with a spectrophotometer (Ferm & Svanberg, 1998). AVOCs and BVOCs (see Table 3 for the list of compounds) were sampled using diffusive Carbopack B adsorbent tubes and analyzed according to the EN ISO 16017-2 standard, where the concentrations of the studied compounds, counted from individual adsorbent tubes, are determined by comparing them to compound-specific standard substances. VOC results are presented as total AVOCs (= T-AVOCs, including all the sampled AVOC compounds) and as total BVOCs (= T-BVOCs, including all the sampled BVOC compounds). Particle pollution levels were measured using passive collectors developed by IVL (Ferm, Watt, O'Hanlon, De Santis & Varotsos, 2006). NO_2 samplers and their analyses were provided by Metropolilab, Helsinki, Finland, O_3 and particle samplers and their analyses by IVL, and VOC samplers and their analyses by Ramboll Analytics, Lahti, Finland.

The sampling of NO_2, O_3 and VOCs is based on molecular diffusion. The method has some limitations, but has been successfully used in numerous studies, with results strongly in line with continuous air monitoring (Ayers, Keywood, Gillett, Manins, Malfroy & Bardsley, 1998; HSY, 2014; Krupa & Legge, 2000). The passive particle sampling method is based on the deposition of particles by impaction and diffusion on a vertically-mounted cylindrical Teflon surrogate surface. The method does not provide information on the specific particle size fractions, but provides the mass of deposited particles on the sampler surface. Mass is calculated by weighing the surrogate surface before and after exposure. The surrogate surfaces are equilibrated for 24 h before weighing in a weighing room at 20°C and 50% relative humidity (Ferm et al., 2006). Ferm et al. (2006) noted that particle deposition on Teflon correlated well with PM_{10} concentrations when samplers were not situated in the immediate vicinity of roads.

2.2. Sampling sites and dates

Ten sampling sites [different from those in Setälä et al. (2013)] in the Helsinki Metropolitan Area (eight in the city of Helsinki, and one each in the neighboring cities of Espoo and Vantaa, Fig. 1b) were established on the northern side of roads oriented in an east-west direction with moderate to heavy traffic flows (Table 1). This ensured that air pollutant collectors resided downwind from traffic-derived air pollutants. There were no major intersections or roads oriented in a south-north direction, or other roads oriented in a west-east direction to the north of the measuring sites that could potentially have biasing effects. Each of the 10 sites consisted of a pair of sampling units placed on the northern side of the road: one unit in an open area and another in a tree-covered area. The sampling sites were approximately level with the road surface. The open areas were meadows, grasslands or other treeless areas. The soil surface at these open areas was either completely pervious or partly impervious with asphalt walking and cycling paths. The tree-covered areas were mature urban forests of mainly broadleaved trees and a rich understorey layer. Although all sites resided in the urban environment, no buildings or other urban infrastructure existed in close proximity to the sites (see e.g., Fig. 1c).

The samplers were mounted under rain shields fixed to 40 cm-long aluminium L-shaped sampler holders (together forming a sampling unit), which were attached to lamp posts or wooden poles in the open areas. In the tree-covered areas the sampler holders were attached to tree trunks directly under the canopy. The shields and sampler holders were manufactured by IVL. The sampling units for NO_2, VOCs and particles were mounted 2.0-3.5 m above ground depending

on a suitable mounting structure. O_3 sampling units were mounted 3.2 m above ground to prevent them from being too close to the ground where O_3 gets depleted (Mills, Pleijel, Büker, Braun, Emberson, Harmens, Hayes, Simpson, Grünhage, Karlsson, Danielsson, Bermejo & Gonzalez Fernandez, 2010). Within each site, the sampling units (open and tree-covered) were always placed at the same distance from the side of the road (a line marking the outer boundary of the road). At different sites, depending on the availability of suitable mounting structures, the sampling unit pairs were situated at slightly different distances from the road side; ranging between 18 and 30 m (mean = 25.6 m). The forest edge in tree-covered areas was, on average, 6.2 m (0 – 14 m) from the road side. The area between the road and the forest edge was open with short grass or meadow vegetation. Measurements were carried out during midsummer when plant leaves were fully developed: NO_2, VOCs and particle levels were measured from 29 May to 26 June, 2013 (28 days) and O_3 was measured from 2 June to 7 July, 2014 (35 days).

A set of environmental variables was quantified at the sites (Table 1): Canopy closure at the tree-covered areas was estimated using two upwards facing photographs taken 1 m above ground. One photograph was taken underneath the sampling unit and the second one 5 m towards the road from the sampling unit. The two photographs represented canopy closure well enough due to the rather homogenous tree/canopy composition within each forested site. The proportion of non-visible sky, a proxy for canopy closure, was calculated using Adobe Photoshop image processing software. The number and size of trees [including trees with a diameter at breast height, DBH > 2.54 cm (= 1 inch)], and whether the trees were deciduous or coniferous, were determined from a sector covering 90˚ from the sampling unit perpendicular towards the road that delineated the area. The number of trees was converted to represent number per unit area

208 (100 m^2 in this case). The extent of ground vegetation (shrubs, bushes, meadow vegetation) was
209 estimated visually at both tree-covered and open areas and classified into dense, intermediate and
210 meager (Table 1).
211
212 The degree of canopy closure was 84.7% ± 8.0 (mean ± SD) in the tree-covered sampling sites.
213 The total number of trees recorded was 73.7 ± 45.5, with large trees (DBH > 32 cm) comprising
214 4.4% (± 5.1) of all the trees. The sampling sites were dominated by deciduous trees (96% ± 7),
215 including forest tree species (*Betula* spp. and *Sorbus aucuparia* being dominant with scattered
216 *Populus* spp. and *Prunus padus*) typical to Southern Finland. Traffic flow data (monthly average,
217 Table 1) were obtained from the City of Helsinki (2012) and the Finnish Transport Agency
218 (2010). Mean annual anthropogenic pollution concentrations, measured at several sampling
219 locations in Helsinki in 2013, were 14–49 µg m^{-3} for NO_2, 39–52 µg m^{-3} for O_3, 2–6 µg m^{-3} for
220 AVOCs (benzene, toluene and xylenes combined) and 11–25 µg m^{-3} for PM_{10} (Air quality in
221 Finland, 2015). Mean annual NO_2, O_3 and PM_{10} concentrations at municipal monitoring stations
222 do not usually exceed annual human health limit values of 40 µg m^{-3}, 120 µg m^{-3} and 40 µg m^{-3},
223 respectively, with the exception of NO_2 in a few highly trafficked locations. Regarding AVOCs,
224 an annual threshold value is available only for benzene (5 µg m^{-3}). For BVOCs no threshold
225 values are available. A wind rose showing the prevailing wind direction and speed during the
226 measuring periods is shown in Fig. 2. The monthly average temperature in Helsinki in June 2013
227 was 18.1 °C and in June 2014 13.6 °C, representing typical temperatures in June in the Helsinki
228 area.
229
230 *2.3. Data analysis*

We analyzed the air pollution data using paired samples *t*-test to determine if there is a difference in pollution levels between the tree-covered and open study areas. We considered *p*-values < 0.05 to indicate statistically significant differences between treatments. Data were $\log_{10}$ transformed to stabilize the variance of individual properties where necessary. Linear regression was applied to detect possible correlations between measured environmental variables and pollution level differences between the tree-covered and open areas. In open areas, the influence of ground vegetation on air pollution was tested using the pollution levels of open areas. T-BVOCs were not tested because BVOCs are emitted mainly by trees and not by shrubs and other typical grassland vegetation. The impact of traffic flow on pollution levels was tested using the actual pollutant levels measured at each sampling point, including both open and tree-covered areas. T-BVOCs were not tested because BVOCs are not traffic-emitted substances. Statistical analyses were performed using SPSS Statistics, version 21.

3. Results

Results for each air pollutant are presented both as means (± SD) of all sites (tree-covered vs. open area comparisons), and for each site separately along the traffic flow gradient (number of motor vehicles day^{-1}) to explore a potential correlation between pollutant levels and traffic flow (Fig. 3). As for total BVOCs (T-BVOCs), values are presented in relation to % canopy closure to depict the association between increasing canopy closure and T-BVOC levels (Fig. 3). Concentrations of the gaseous pollutants did not differ significantly between tree-covered and open areas (NO_2, 2.6% higher in tree-covered areas, $p = 0.407$; O_3, 3.8% lower in tree-covered

areas, $p = 0.177$; total AVOC (T-AVOC), 2.7% lower in tree-covered areas, $p = 0.718$; T-BVOC, 9.5% higher in tree-covered areas, $p = 0.432$) (Fig. 3a-d). Thus, tree-cover had no effect on the concentrations of gaseous pollutants, while traffic flow explained most of the variation in NO_2 concentrations and some of the variation in O_3 concentrations between sites (Table 2). For T-AVOCs and particle levels, no such correlation was evident, neither in tree-covered nor in open areas (Table 2). A detailed listing of the constituent AVOCs and BVOCs and their proportions are shown in Table 3. The proportions of AVOC and BVOC constituents were insensitive to the presence of trees (results not shown).

In contrast to gaseous pollutants, particle pollution levels differed statistically significantly between the tree-covered and open study areas: particle levels were, on average, 23% ($p = 0.023$) lower in tree-covered areas than in open areas (Fig. 3e). None of the measured vegetation properties correlated statistically significantly with the difference in particle levels between the tree-covered and open areas (Table 2). As NO_2, O_3, T-AVOC and T-BVOC concentrations did not differ statistically significantly between tree-covered and open areas, the relationships between their differences and vegetation properties could not be tested.

None of the vegetation properties measured in the tree-covered areas correlated statistically significantly with T-BVOC levels (results not shown), although there appears to be a trend in T-BVOC levels for total number of trees ($R = 0.616$, $p = 0.078$) and % canopy closure ($R = 0.546$, $p = 0.129$).

4. Discussion

Results from our study, conducted under northern summertime conditions (June), suggest that forest vegetation in near-road urban environments does not improve local air quality in terms of gaseous (NO_2, O_3, AVOCs) air pollutants, thus corroborating earlier findings in late summer (August-September) in two Finnish cities (Setälä et al., 2013). In a similar study in Sweden, but only from one measurement site, Grundström and Pleijel (2014) found slightly (7%) reduced NO_2 concentrations in the forest canopy. However, besides the canopy effect, this reduction may have resulted from the 4 m difference in distance between their open and canopy sampling points from a heavy traffic road (the latter being further away from the road) (see e.g. HSY, 2014). In the same study, the authors did not detect reduced O_3 concentrations in the canopy (Grundström & Pleijel, 2014), which is in line with our results. Fantozzi, Monaci, Blanusa & Bargagli (2015) found lower NO_2 concentrations under the canopies of Mediterranean trees (evergreen *Quercus ilex* L.) growing 1-10 m from a road compared to a nearby open-field transect. However, reduced O_3 concentrations in the canopy were observed only during post-summer rainfalls (Fantozzi et al. 2015), indicating that the impact of vegetation on gaseous pollution concentrations may also depend on the type of local vegetation and climatic conditions. On the other hand, Harris and Manning (2010) found, also using passive samplers, higher NO_2 and lower O_3 levels within urban tree canopies than outside them. They suggested that this results from NO_x/O_3 chemistry related to gas interactions between soil and the air, as described by Fowler (2002). Although the three gases in our study were sampled at the same locations, O_3 was collected a year later than NO_2 and VOC preventing us from comparing NO_2 and VOC levels directly with those of O_3. Furthermore, using data collected during one month only to unravel complex interactions

between NO_2, O_3 and VOCs is challenging due to the rapid and complex dynamics of these compounds in the air.

Our results, however, do support earlier studies showing that trees can mitigate problems associated with particulate air pollution (e.g. Beckett et al., 2000a,b; Cavanagh et al., 2009; Tallis, Taylor, Sinnett & Freer-Smith, 2011), particularly in the near-road environment (Baldauf, Thoma, Khlystov, Isakov, Bowker, Long & Snow, 2008; Islam, Rahman, Bahar, Habib, Ando & Hattori, 2012; Maher, Ahmed, Davison, Karloukovski & Clarke, 2013; Setälä et al., 2013; Steffens, Wang & Zhang, 2012), although the tree effect can depend on environmental conditions such as wind direction in relation to pollution source, as well as particle size (Brantley et al., 2014; Hagler, Lin, Khlystov, Baldauf, Isakov, Faircloth & Jackson, 2012; Tong, Whitlow, MacRae, Landers & Harada, 2015). Although the method used in our study does not allow for the measurement of size fractions of the collected particles, it is likely that coarse particles, most likely road dust, were emphasized in the mass deposition (Ferm et al., 2006); the Teflon sampling surfaces were visibly dirtier close to the road than further away. However, regarding smaller particles, the situation can be different: Tong et al. (2015) investigated the dispersion of particulates near roads using aerosol spectrometers in brief monitoring campaigns and found that $PM_{2.5}$ concentrations were higher along a transect with trees downwind from the road and declined less sharply than along open transects without trees. Also, as noted by Setälä et al. (2013), particle levels, measured with passive samplers, were notably and significantly lower in tree-covered areas compared to open areas, but often inconsistent with particle data gathered using “active” collecting devices, which can specify particle size fractions and produce results both in mass and number. Considering the particle deposition results and the measuring

322 methodology in this study, it should be noted that particles that can enter throughout the human
323 respiratory system are smaller than 2.5 µm in diameter, and these are easily outweighed by larger
324 particles.
325
326 Sampling in the current study was done in June, i.e. during midsummer in Finland when total
327 leaf area, as well as gas exchange between leaves and ambient air, is high (Rautiainen,
328 Heiskanen & Korhonen, 2012). However, when comparing our results to Setälä et al. (2013), in
329 which sampling took place in late summer (from early August to early September) when leaf
330 activity is ceasing, it is interesting to note that road-side vegetation did not reduce NO_2 and
331 AVOC concentrations neither during mid- nor late summer seasons. In order to explore the
332 canopy effect for the entire growth period, the duration of measuring campaigns during the same
333 year should extend over the entire leaf period.
334
335 Estimates on the ability of trees to absorb anthropogenic VOCs are based on a few laboratory
336 incubation studies (Cornejo, Munoz, Ma & Stewart, 1999; Keymeulen et al., 1995; Yang,
337 Pennisi, Son & Kays, 2009). To our knowledge, the fate of AVOCs in relation to urban
338 vegetation has only been investigated in one study in Las Vegas, U.S. (Hiatt, 1998), where
339 samples of air and leaves of several tree species were analyzed. Hiatt (1998) showed that several
340 local tree species can absorb AVOCs according to existing models. However, our results indicate
341 that the potential of trees to create areas of lower AVOC concentrations at the local scale in
342 northern climates is meager, at least in urbanized sites where deciduous trees constitute most of
343 the vegetation, corroborating Setälä et al. (2013).
344

Concentrations of BVOCs appeared to be relatively low at most of the study sites (often barely above the detection limit), and were not significantly different between the open and tree-covered areas. Although conifers in Nordic regions are efficient emitters of monoterpenes, some deciduous tree species, such as *Betula pendula*, *B. pubescens*, *Populus tremula* and *Salix* sp., are also known to emit monoterpenes (Hakola, Rinne & Laurila, 1999; Lindfors & Laurila, 2000). Deciduous trees made up most of the canopy cover at our study sites, but BVOC concentrations were equally low in most of the open and tree-covered sites.

That concentrations of gaseous pollutants appeared to be unresponsive to forest vegetation, while particle pollution levels were clearly reduced by tree-cover, can be due to the inefficiency of northern vegetation to absorb and process gaseous pollutants, such as NO_2, O_3 and AVOCs. The amount of pollutants absorbed by stomatal intake seems to be irrelevant in the context of ambient concentrations. However, even if the vegetation could absorb these pollutants efficiently, it is possible that reduced air flow within tree-covered sites (Belcher, Harman & Finnigan, 2012; Gromke & Ruck, 2009; Wuyts, Verheyen, De Schrijver, Cornelis & Gabriels, 2008) can increase pollutant levels within the canopy and thus have negative impacts on local air quality (see Setälä et al., 2013; Viippola et al., 2016; Vos et al., 2013), while in open areas the polluted air mass is mixed by wind and diluted more rapidly. Such an indirect effect of vegetation on local air quality is seldom reported in the literature and merits more research.

The clear reduction in particle levels at tree-covered sites did not relate to any of the measured vegetation properties. It is possible that the vegetation parameters measured here were not instrumental in creating potential variation in air particulate levels and more parameters would

368 have been needed to tackle this variation. Nevertheless, the reduction in particle levels is best
369 explained by either effective deposition of large (and heavy) particles on vegetation surfaces or
370 perhaps - more importantly - by reduced ventilation under the canopy. Wind speed is known to
371 be lower under thick canopies compared to open, treeless areas (Belcher et al., 2012; Setälä et
372 al., 2013; Wania, Bruse, Blond & Weber, 2012), which likely prevents road dust from dispersing
373 further away from the road in tree-covered areas.
374
375 Due to the fact that air pollution patterns can be shaped by wind conditions in urban areas (Choi,
376 He, Barbesant, Kozawa, Mara, Winer & Paulson, 2012; Kozawa, Winer & Fruin, 2012;
377 McNabola, Broderick & Gill, 2009), the placement of sampling devices in relation to prevailing
378 wind patterns deserved attention in our study set-up. As the prevailing wind direction (long-term
379 average) in June in Helsinki is from the south or south-west, all sampling sites were placed
380 downwind from the pollution source. Wind direction, however, varied considerably during the
381 one-month measuring periods in 2013 and 2014 and no clear consistency in wind direction at the
382 study region was evident (Fig. 2). However, south-western and eastern winds dominated, and
383 only a small percentage of winds blew from the north in June 2013. Thus, for most of that
384 campaign period, our sampling units were downwind or at least in a neutral position, but clearly
385 not upwind, in relation to pollution sources. In June 2014, when O_3 was measured, winds blew
386 from almost all directions. Moreover, the relatively long sampling period used is bound to
387 diminish the impacts of short-term wind direction changes and local eddies on our results. The
388 concentrations of NO_2, O_3 and AVOCs were in line with the available mean annual and monthly
389 (June 2013) concentration data from Helsinki, and always below the limit values for human
390 health (Air quality in Finland, 2015; HSY, 2014).

5. Conclusions

The current study conducted in Helsinki corroborates results from other studies in Nordic urban environments (Setälä et al., 2013; Viippola et al., 2016); the impact of the tree canopy, at least in near-road environments without buildings, is negligible regarding the concentrations of certain gaseous air pollutants. Alternatively, it may be that these gaseous pollutants were absorbed to some extent by the canopy, but not sufficiently so to compensate for increased concentrations due to reduced air-flow in tree-covered areas (see Janhäll, 2015). However, the levels of coarse particulate matter were reduced by the presence of trees. The methodology used does not allow for the extrapolation of this conclusion to fine particles. Our results - obtained from the period when gas exchange between foliage and the atmosphere is most active - thus suggest that forest vegetation does not necessarily reduce air pollutant levels in urban areas. However, further empirical field research on the mechanisms and factors contributing to the various direct and indirect impacts of vegetation on air pollutant levels is needed.

Acknowledgments

We thank Johan Kotze for checking the English and for many helpful comments. This study was funded by the Helsinki Metropolitan Region Urban Research Program and the Helsinki University Centre for Environment (HENVI, ENSURE research programme).

References

1. Air quality in Finland (2015). Retrieved January 2, 2015 from - http://www.ilmanlaatu.fi

2. Ayers, G. P., Keywood, M. D., Gillett, R., Manins, P. C., Malfroy, H., Bardsley, T. (1998). Validation of passive diffusion samplers for SO_2 and NO_2. *Atmospheric Environment*, 32, 3587–3592.

3. Baldauf, R., Thoma, E., Khlystov, A., Isakov, V., Bowker, G., Long, T., & Snow, R. (2008). Impact of noise barriers on near-road air quality. *Atmospheric Environment*, 42, 7502–7507.

4. Baumgardner, D., Varela, S., Escobedo, F. J., Chacalo, A., & Ochoa, C. (2012). The role of peri-urban forest on air quality improvement in the Mexico City megalopolis. *Environmental Pollution*, 163, 174−183.

5. Beckett, K. P., Freer-Smith, P. H., & Taylor, G. (2000a). The capture of particulate pollution by trees at five contrasting urban sites. *Arboricultural Journal*, 24, 209–230.

6. Beckett, K. P., Freer-Smith, H. P., & Taylor, G., (2000b). Particulate pollution capture by urban trees: effect of species and windspeed. *Global Change Biology*, 6**,** 995–1003.

7. Belcher, S. E., Harman, I. N., & Finnigan, J. J. (2012). The wind in the willows: flows in forest canopies in complex terrain. *Annual Review of Fluid Mechanics*, 44, 479–504.

8. Brantley, H. L., Hagler, G. S. W., Deshmukh, P. J., & Baldauf, R. W. (2014). Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter. *Science of the Total Environment*, 468-469, 120–129.

9. Calfapietra, C., Fares, S., Manes, F., Morani, A., Sgrigna, G., & Loreto, F. (2013). Role of Biogenic Volatile Compounds (BVOC) emitted by urban trees on ozone concentration in cities: A review. *Environmental Pollution*, 183, 71–80.

10. Cavanagh, J.-O. E., Zawar-Reza, P., & Wilson, J. G. (2009). Spatial attenuation of ambient particulate matter air pollution within an urbanised forest patch. *Urban Forestry & Urban Greening*, 8, 21–30.

11. Chaparro, L., & Terradas, J. (2009). *Ecological Services of Urban Forest in Barcelona*. Centre de Recerca Ecologica in Aplicacions Forestals, Universitat Autonoma de Barcelona, Spain.

12. Chaparro-Suarez, I. G., Meixner, F. X., & Kesselmeier, J. (2011). Nitrogen dioxide (NO_2) uptake by vegetation controlled by atmospheric concentrations and plant stomatal aperture. *Atmospheric Environment*, 45, 5742–5750.

13. Choi, W., He, M., Barbesant, V., Kozawa, K. H., Mara, S., Winer, A. M., & Paulson, S. E. (2012). Prevalence of wide area impacts downwind of freeways under pre-sunrise stable atmospheric conditions. *Atmospheric Environment*, 62, 318−327.

14. City of Helsinki (2012). *Traffic volumes on main streets of Helsinki, September 2012*. City Planning Department, Transportation and Travel Planning.

15. Cornejo, J. J., Munoz, F. G., Ma, C. Y., & Stewart, A. J. (1999). Studies on the decontamination of air by plants. *Ecotoxicology*, 8, 311–320.

16. Doty, S. L., James, C. A., Moore, A. L., Vajzovic, A., Singleton, G. L., Ma, C., Khan, Z., Xin, G., Kang, J. W., Park, J. Y., Meilan, R., Strauss, S. H., Wilkerson, J., Farin, F., & Strand, S. E. (2007). Enhanced phytoremediation of volatile environmental pollutants with transgenic trees. *PNAS*, 104, 16816–16821.

17. EEA (2014). *Air quality in Europe – 2014 report*. European Environment Agency EEA Report No 5/2014. Retrieved January 1, 2015 from - http://www.eea.europa.eu/publications/air-quality-in-europe-2014

18. Fantozzi, F., Monaci, F., Blanusa, T., & Bargagli, R. (2015). Spatio-temporal variations of ozone and nitrogen dioxide concentrations under urban trees and in a nearby open area. *Urban Climate*, 12, 119–127.

19. Ferm, M., & Svanberg, P.-A. (1998). Cost-efficient techniques for urban- and background measurements of SO_2 and NO_2. *Atmospheric Environment*, 32, 1377–1381.

20. Ferm, M., Watt, J., O'Hanlon, S., De Santis, F., & Varotsos, C. (2006). Deposition measurement of particulate matter in connection with corrosion studies. *Analytical and Bioanalytical Chemistry*, 384, 1320–1330.

21. Finnish Transport Agency (2010). *Traffic flow map of Uusimaa region 2010*. Retrieved 5 September, 2016 from - http://www.liikennevirasto.fi/tilastot/tietilastot/liikennemaarakartat1/vanhat-liikennemaarakartat

22. Freer-Smith, P. H., Beckett, K. P., & Taylor, G. (2005). Deposition velocities to *Sorbus aria*, *Acer campestre*, *Populus deltoids* × *trichocarpa* 'Beaupré', *Pinus nigra* and × *Cupressocyparis leylandii* for coarse, fine and ultra-fine particles in the urban environment. *Environmental Pollution*, 133, 157–167.

23. Fowler, D. (2002). Pollutant deposition and uptake by vegetation. In J. N. B. Bell, & M. Treshow (Eds.), *Air Pollution and Plant Life* (pp. 43–67). John Wiley and Sons, Ltd., New York.

24. Gromke, C., & Ruck, B. (2009). On the impact of trees on dispersion processes of traffic emissions in street canyons. *Boundary-Layer Meteorology*, 131, 19–34.

25. Grundström, M., & Pleijel, H. (2014). Limited effect of urban tree vegetation on NO_2 and O_3 concentrations near a traffic route. *Environmental Pollution*, 189, 73–76.

26. Hagler, G. S. W., Lin, M. Y., Khlystov, A., Baldauf, R. W., Isakov, V., Faircloth, J., & Jackson, L. E. (2012). Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentration under a variety of wind conditions. *Science of the Total Environment*, 419, 7–15.

27. Hakola, H., Rinne, J., & Laurila, T. (1999). The VOC emission rates of boreal deciduous trees. In T. Laurila, & V. Lindfors (Eds.), *Biogenic VOC emissions and photochemistry in the boreal regions of Europe* (pp. 21–28). Air Pollution Research Report 70, Commission of the European Communities, Luxembourg.

28. Harris, T. B., & Manning, W. J. (2010). Nitrogen dioxide and ozone levels in urban tree canopies. *Environmental Pollution*, 158, 2384–2386.

29. Hiatt, M. H. (1998). Bioconcentration factors for volatile organic compounds in vegetation. *Analytical Chemistry*, 70, 851–856.

30. Hirabayashi, S., Kroll, C. N., & Nowak, D. J. (2012). Development of a distributed air pollutant dry deposition modeling framework. *Environmental Pollution*, 171, 9–17.

31. Hofman, J., Stokkaer, I., Snauwaert, L., & Samson, R. (2013). Spatial distribution assessment of particulate matter in an urban street canyon using biomagnetic leaf monitoring of tree crown deposited particles. *Environmental Pollution*, 183, 123–132.

32. HSY (Helsinki Region Environmental Services Authority) (2014). *Ilmanlaatu pääkaupunkiseudulla vuonna 2013* (*Air Quality in the Helsinki Metropolitan Area in*

2013). HSY publications 3/2014. [in Finnish with an abstract in English] Retrieved 5 September, 2016 from - https://www.hsy.fi/sites/Esitteet/EsitteetKatalogi/Julkaisusarja/3_2014_Ilmanlaatu_paakaupunkiseudulla_2013.pdf

33. Islam, M. N., Rahman, K.-S., Bahar, M. M., Habib, M. A., Ando, K., & Hattori, N. (2012). Pollution attenuation by roadside greenbelt in and around urban areas. *Urban Forestry & Urban Greening*, 11, 460–464.

34. Janhäll, S. (2015). Review on urban vegetation and particle pollution - Deposition and dispersion. *Atmospheric Environment*, 105, 130–137.

35. Jim, C. Y., & Chen, W. Y. (2008). Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China). *Journal of Environmental Management*, 88, 665–676.

36. Keymeulen, R., Schamp, N., & Van Langenhove, H. (1995). Uptake of gaseous toluene in plant leaves: a two compartment model. *Chemosphere*, 31, 3961–3975.

37. Kozawa, H. K., Winer, A. M., & Fruin, S. A. (2012). Ultrafine particle size distributions near freeways: Effects of differing wind directions on exposure. *Atmospheric Environment*, 63, 250–260.

38. Krupa, S. V., & Legge, A. H. (2000). Passive sampling of ambient, gaseous air pollutants: An assessment from an ecological perspective. *Environmental Pollution*, 107, 31–45.

39. Lindfors, V., & Laurila, T. (2000). Biogenic volatile organic compound (VOC) emissions from forests in Finland. *Boreal Environment Research*, 5, 95–113.

40. Loreto, F., & Schnitzler, J.-P. (2010). Abiotic stresses and induced BVOCs. *Trends in Plant Science*, 15, 154–166.

41. Maher, B. A., Ahmed, I. A. M., Davison, B., Karloukovski, V., & Clarke, R. (2013) Impact of roadside tree lines on indoor concentrations of traffic-derived particulate matter. *Environmental Science & Technology*, 47, 13737–13744.

42. Manes, F., Incerti, G., Salvatori, E., Vitale, M., Ricotta, C., & Costanza, R. (2012). Urban ecosystem services: tree diversity and stability of tropospheric ozone removal. *Ecological Applications*, 22, 349–360.

43. McDonald, A. G., Bealey, W. J., Fowler, D., Dragosits, U., Skiba, U., Smith, R. I., Donovan, R. G., Brett, H. E., Hewitt, C. N., & Nemitz, E. (2007). Quantifying the effect of urban tree planting on concentrations and depositions of PM_{10} in two UK conurbations. *Atmospheric Environment*, 41, 8455–8467.

44. McNabola, A., Broderick, B. M., & Gill, L. W. (2009). A numerical investigation of the impact of low boundary walls on pedestrian exposure to air pollutants in urban street canyons. *Science of The Total Environment*, 407, 760–769.

45. Mills, G., Pleijel, H., Büker, P., Braun, S., Emberson, L., Harmens, H., Hayes, F., Simpson, D., Grünhage, L., Karlsson, P.-E., Danielsson, H., Bermejo, V., & Gonzalez Fernandez, I. (Eds.) (2010). *Chapter 3 of the LRTAP Convention Manual on Methodologies and Criteria for Modelling and Mapping Critical Loads & Levels and Air Pollution Effects, Risks and Trends*. Retrieved 5 September, 2016 from - http://www.rivm.nl/media/documenten/cce/manual/Ch3revisedsummer2010updatedJune2011.pdf

46. Morani, A., Nowak, D. J., Hirabayahsi, S., & Calfapietra, C. (2011). How to select the best tree planting locations to enhance air pollution removal in the MillionTreesNYC initiative. *Environmental Pollution*, 159, 1040–1047.

47. Nowak, D. J. (2006). Institutionalizing urban forestry as a "biotechnology" to improve environmental quality. *Urban Forestry & Urban Greening*, 5, 93–100.

48. Nowak , D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, 4, 115–123.

49. Nowak, D. J., Crane, D. E., Stevens, J. C., Hoehn, R. E., Walton, J. T., & Bond, J. (2008). A ground-based method of assessing urban forest structure and ecosystem services. *Arboriculture & Urban Forestry*, 34, 347–358.

50. Nowak, D. J., Hirabayashi, S., Bodine, A., & Hoehn, R. (2013). Modeled $PM_{2.5}$ removal by ten U.S. cities and associated health effects. *Environmental Pollution*, 178, 395–402.

51. Paoletti, E., De Marco, A., Beddows, D. C. S., Harrison, R. M., & Manning, W.J. (2014). Ozone levels in European and USA cities are increasing more than at rural sites, while peak values are decreasing. *Environmental Pollution*, 192, 295–299.

52. Pataki, D. E., Alberti, M., Cadenasso, M. L., Felson, A. J., McDonnell, M. J., Pincetl, S., Pouyat, R. V., Setälä, H., & Whitlow, T. H. (2013). City trees: Urban greening needs better data. *Nature*, 502, 624.

53. Pataki, D. E., Carreiro, M. M., Cherrier, J., Grulke, N. E., Jennings, V., Pincetl, S., Pouyat, R. V., Whitlow, T. H., & Zipperer, W. C. (2011). Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Frontiers in Ecology and the Environment*, 9, 27–36.

54. Rautiainen, M., Heiskanen, J., & Korhonen, L. (2012). Seasonal changes in canopy leaf area index and MODIS vegetation products for a boreal forest site in Central Finland. *Boreal Environment Research*, 17, 72–84.

55. Rondón, A., & Granat, L. (1994). Studies on the dry deposition of NO_2 to coniferous species at low NO_2 concentrations. *Tellus*, 46B, 339–352.

56. Räsänen, J. V., Holopainen, T., Joutsensaari, J., Ndam, C., Pasanen, P., Rinnan, Å., & Kivimäenpää, M. (2013). Effects of species-specific leaf characteristics and reduced water availability on fine particle capture efficiency of trees. *Environmental Pollution*, 183, 64–70.

57. Setälä, H., Viippola, V., Rantalainen, A.-L., Pennanen, A., & Yli-Pelkonen, V. (2013). Does urban vegetation mitigate air pollution in northern conditions? *Environmental Pollution*, 183, 104–112.

58. Steffens, J. T., Wang, Y. J., & Zhang, K. M. (2012). Exploration of effects of a vegetation barrier on particle size distribution in a near-road environment. *Atmospheric Environment*, 50, 120–128.

59. Streiling, S., & Matzarakis, A. (2003). Influence of single and small clusters of trees on the bioclimate of a city: A case study. *Journal of Arboriculture*, 29, 309–316.

60. Takahashi, M., Higaki, A., Nohno, M., Kamada, M., Okamura, Y., Matsui, K., Kitani, S., & Morikawa, H. (2005). Differential assimilation of nitrogen dioxide by 70 taxa of roadside trees at an urban pollution level. *Chemosphere*, 61, 633–639.

61. Tallis, M., Taylor, G., Sinnett, D., & Freer-Smith, P. (2011). Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. *Landscape and Urban Planning*, 103, 129–138.

62. Tong, Z., Whitlow, T. H., MacRae, P. F., Landers, A. J., & Harada, Y. (2015). Quantifying the effect of vegetation on near-road air quality using brief campaigns. *Environmental Pollution*, 201, 141–149.

63. Viippola, V., Rantalainen, A.-L., Yli-Pelkonen, V., Tervo, P., & Setälä, H. (2016). Gaseous polycyclic aromatic hydrocarbon concentrations are higher in urban forests than adjacent open areas during summer but not in winter - Exploratory study. *Environmental Pollution*, 208, 233–240.

64. Vos, P. E. J., Maiheu, B., Vankerkom, J., & Janssen, S. (2013). Improving local air quality in cities: To tree or not to tree? *Environmental Pollution*, 183, 113−122.

65. Wang, H., Zhou, W., Wang, X., Gao, F., Zheng, H., Tong, L., & Ouyang, Z. (2012). Ozone uptake by adult urban trees based on sap flow measurement. *Environmental Pollution*, 162, 275–286.

66. Wania, A., Bruse, M., Blond, N., & Weber, C. (2012). Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations. *Journal of Environmental Management*, 94, 91–101.

67. Weber, F., Kowarik, I., & Säumel, I. (2014). Herbaceous plant as filters: Immobilization of particulates along urban street corridors. *Environmental Pollution*, 186, 234–240.

68. Whitlow, T. (2009). *Determining the fate of $PM_{2.5}$ particles following capture by leaves*. Ithaca, NY: Cornell University. Final Technical Report. Retrieved 5 September, 2016 from - http://www.urbanforestrysouth.org/research/nucfac/determining-the-fate-of-pm-2-5-particles-following-capture-by-leaves-05-dg-11233225-228

69. Wuyts, K., Verheyen, K., De Schrijver, A., Cornelis, W. M., & Gabriels, D. (2008). The impact of forest edge structure on longitudinal patterns of deposition, wind speed, and turbulence. *Atmospheric Environment*, 42, 8651–8660.

70. Yang, D. S., Pennisi, S. V., Son, K.-C., & Kays, S. J. (2009). Screening indoor plants for volatile organic pollutant removal efficiency. *HortScience*, 44, 1377–1381.

71. Yin, S., Shen, Z., Zhou, P., Zou, X., Che, S., & Wang, W. (2011). Quantifying air pollution attenuation within urban parks: An experimental approach in Shanghai, China. *Environmental Pollution*, 159, 2155–2163.

LIST OF TABLES

Table 1. Environmental variables measured at the 10 study sites in the Helsinki Metropolitan Area arranged by ascending traffic flow (number of motor vehicles day^{-1}, monthly average for June). Values referring to canopy closure, trees and ground vegetation were estimated from a sector covering 90 degrees from the sampling unit towards the road that delineated the area. Trees with a diameter at breast height (DBH) of < 2.54 cm (= 1 inch) are not included.

Site	Canopy closure (%)	Total nr. of trees 100 m^{-2}	Nr. of trees with DBH > 32 cm 100 m^{-2}	Tree-covered area - ground vegetation	Open area - ground vegetation	Traffic flow
1	71	13.0	0	dense	dense	8 000
2	75	7.0	0.3	intermediate	dense	14 100
3	95	19.4	1.2	meager	intermediate	14 700
4	82	17.6	0.6	intermediate	intermediate	14 800
5	89	7.4	0.4	intermediate	dense	52 600
6	94	3.3	0.6	intermediate	dense	58 500
7	88	13.8	0	meager	intermediate	64 100
8	78	7.8	0	intermediate	meager	65 000
9	89	5.8	0.5	dense	dense	91 600
10	87	21.4	0.2	intermediate	intermediate	102 400

Table 2. Relationship between vegetation properties and the statistically significant air quality difference of particle levels*. The difference is calculated by subtracting particle levels detected in the tree-covered areas from that in the open areas. Linear regression was used to detect relationships and their statistical significances. The influence of ground vegetation of the open areas was tested using the pollution levels of the open areas (except for T-BVOCs that are mainly emitted by trees). The impact of traffic flow on pollution levels (except for T-BVOCs that are not traffic-emitted) was tested using the actual pollutant levels measured at each sampling point, including both open and tree-covered areas. Statistically significant *R* values are marked in bold.

* = Regarding NO_2, O_3, T-AVOCs and T-BVOCs, the differences between tree-covered and open areas were not statistically significant, and thus the relationships between their differences and vegetation properties were not tested (reason for blank lines).
[a] $n = 10$.
[b] For traffic flow, $n = 20$, except for T-AVOC ($n = 19$).

		Canopy closure [a]	Total nr of trees 100 m^{-2} [a]	Nr of trees with DBH > 32 cm 100 m^{-2} [a]	Tree-covered area's ground vegetation [a]	Open area's ground vegetation [a]	Traffic flow[b]
P-dep.	*R*	0.023	0.484	0.090	0.036	0.138	0.024
	p	0.950	0.157	0.804	0.921	0.704	0.920
NO_2	*R*	–	–	–	–	0.130	**0.787**
	p	–	–	–	–	0.720	**<0.001**
O_3	*R*	–	–	–	–	0.074	**0.545**
	p	–	–	–	–	0.839	**0.013**
T-AVOC	*R*	–	–	–	–	0.169	0.207
	p	–	–	–	–	0.642	0.395

Table 3. List of anthropogenic (AVOC) and biogenic (BVOC) volatile organic compounds and their relative proportions in the samples. Values shown are mean proportions of all the samples collected at the tree-covered and open areas.

AVOC	proportion
Toluene	34 %
Benzene	12 %
Ethylbenzene	7.7 %
o-xylene	9.7 %
m/p-xylene	22 %
Styrene	2.3 %
Ethyl *tert-butyl* ether	0.9 %
Propylbenzene	1.6 %
2-Ethyltoluene	2.9 %
3-Ethyltoluene	5.2 %
4-Ethyltoluene	1.8 %
BVOC	
a-pinene	47 %
b-pinene	13 %
d-carene	13 %
limonene	26 %

LIST OF FIGURES

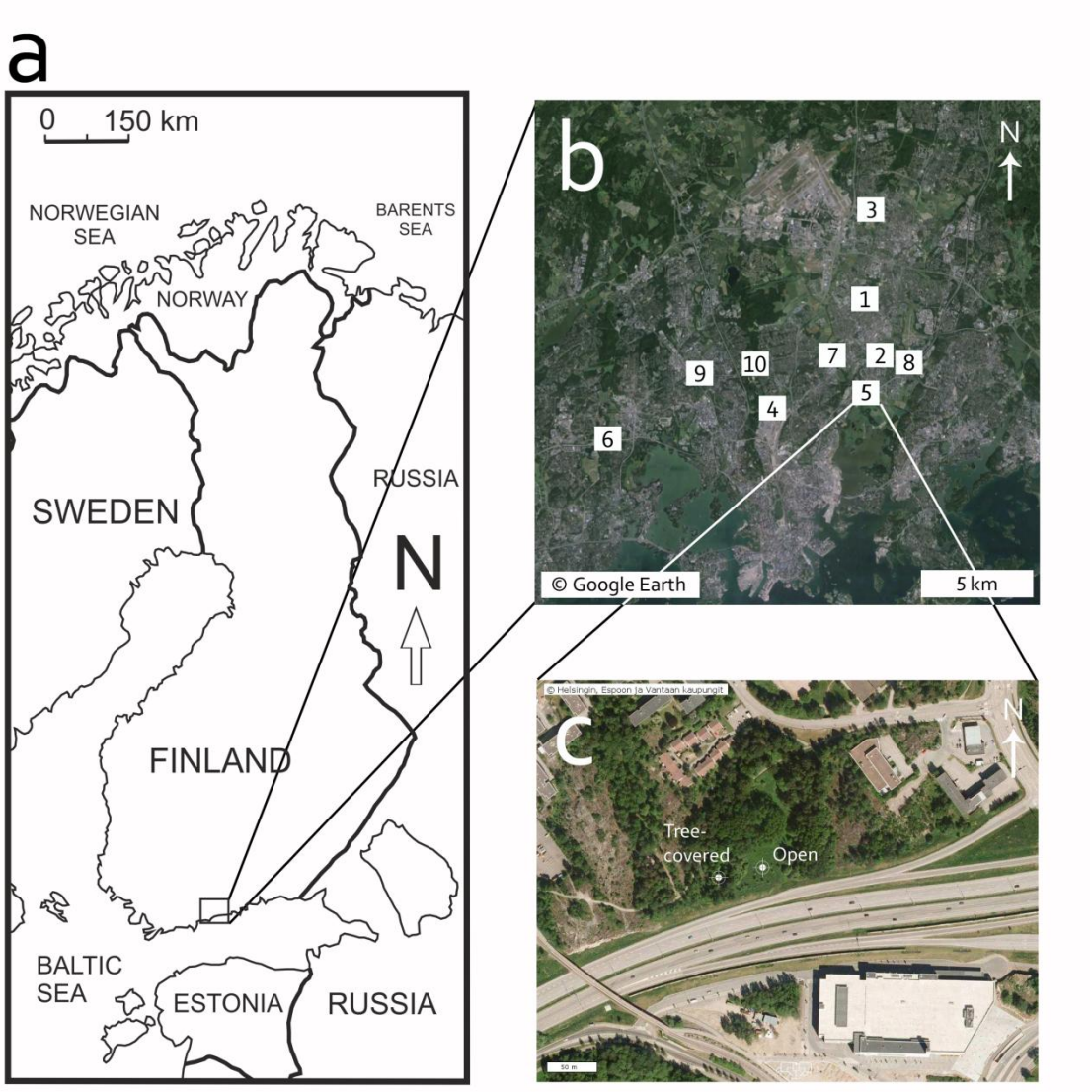

Fig. 1. (a) A map of Finland with (b) an aerial image of the Helsinki Metropolitan Area displaying locations of the ten sampling sites (1 – 10), and (c) an aerial image of one of the sampling sites (site 5) as an example. At each of the 10 sites, air quality was measured in one tree-covered and one open area. At site 5, sampling units were placed ca. 30 m from the road edge.

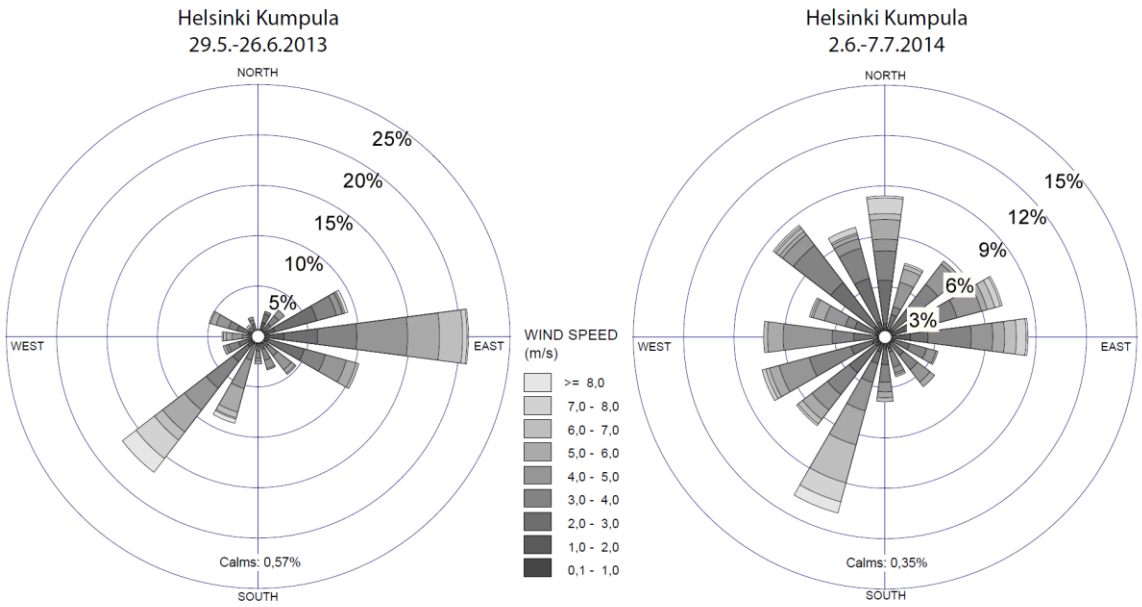

Fig. 2. Wind direction and speed during 29 May – 26 June, 2013 and 2 June – 7 July, 2014 in Helsinki (Kumpula measuring station). Data were provided by the Finnish Meteorological Institute (FMI).

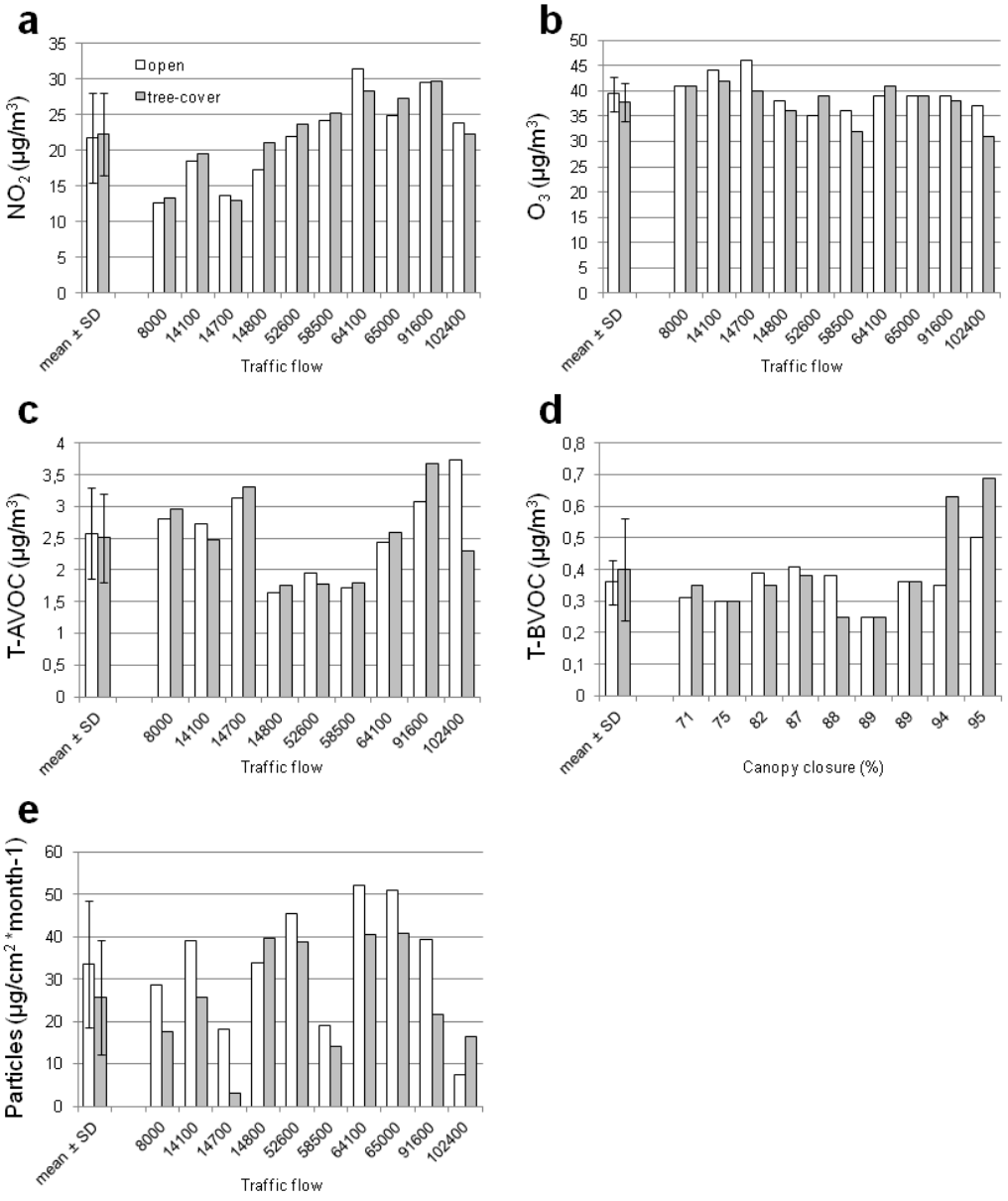
a
NO2 (µg/m3)
open
tree-cover
mean ± SD
8000
14100
14700
14800
52600
58500
64100
65000
91600
102400
Traffic flow
b
O3 (µg/m3)
Traffic flow
c
T-AVOC (µg/m3)
Traffic flow
d
T-BVOC (µg/m3)
71
75
82
87
88
89
89
94
95
Canopy closure (%)
e
Particles (µg/cm2*month-1)
Traffic flow

Fig. 3. Concentrations of (a) NO_2, (b) O_3, (c) total AVOCs, (d) total BVOCs and (e) levels of particles (mass of airborne particles deposited on the sampler) in open (white bars) and tree-covered (grey bars) areas. The first pair of bars in each panel refers to mean ± SD (n = 10, except for total AVOCs and total BVOCs where n = 9 due to a lost VOC sample in one tree-covered study area) pollution levels of all 10 study sites. The rest of the bar pairs describe each study site separately. The sites are presented in relation to increasing traffic flow (number of motor vehicles day^{-1}), except for T-BVOCs (panel d), where data are presented in relation to % canopy closure.