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

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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 (NO₂, ground-level O₃, 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 (NO₂), ground-level ozone (O₃), 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 NO₂ (Chaparro-Suarez, Meixner & Kesselmeier, 2011; Rondón & Granat, 1994; Takahashi, Higaki, Nohno, Kamada, Okamura, Matsui, Kitani & Morikawa, 2005), O₃ (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 ($\text{NO} + \text{NO}_2$), 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

be improved by the presence of vegetation in the urban environment, where pollutant concentrations are high (e.g. Baumgardner, Varela, Escobedo, Chacalo & Ochoa, 2012; Hirabayashi, Kroll & Nowak, 2012; McDonald, Bealey, Fowler, Dragosits, Skiba, Smith, Donovan, Brett, Hewitt & Nemitz, 2007; Morani, Nowak, Hirabayashi & Calfapietra, 2011; Nowak, Hirabayashi, Bodine & Hoehn, 2013).

Only a few studies exist in which pollutant levels have been measured locally, e.g. within a forest or park canopy and compared to pollution levels in adjacent open areas (see Brantley, Hagler, Deshmukh & Baldauf, 2014; Cavanagh, Zawar-Reza & Wilson, 2009; Freer-Smith, Beckett & Taylor, 2005; Harris & Manning, 2010; Setälä, Viippola, Rantalainen, Pennanen & Yli-Pelkonen, 2013; Streiling & Matzarakis, 2003; Viippola, Rantalainen, Yli-Pelkonen, Tervo & Setälä, 2016; Yin, Shen, Zhou, Zou, Che & Wang, 2011). As such, to enhance our understanding on the uptake, deposition, and re-suspension rates of pollutants by urban vegetation, more on-site, small-scale measuring campaigns are needed (Pataki et al., 2011, 2013; Whitlow, 2009).

Our main objective is to explore the ability of urban vegetation to purify gaseous and particulate air pollutants of anthropogenic, mostly traffic-derived origin under northern summertime conditions in the near-road environment in Finland. This study builds on the same empirical principles as applied by Setälä et al. (2013), in which air pollutant levels (concentrations of NO₂ and VOCs and mass deposition of particles) were measured in open and tree-covered areas in late summer and winter using passive samplers in urban near-road environments in two cities (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 (NO₂), ii) ground-level ozone (O₃), 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 NO₂ and O₃ 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). NO₂ samplers and their analyses were provided by Metropolilab, Helsinki, Finland, O₃ and particle samplers and their analyses by IVL, and VOC samplers and their analyses by Ramboll Analytics, Lahti, Finland.

The sampling of NO₂, O₃ 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 PM₁₀ 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 NO₂, VOCs and particles were mounted 2.0-3.5 m above ground depending

on a suitable mounting structure. O₃ sampling units were mounted 3.2 m above ground to prevent them from being too close to the ground where O₃ 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: NO₂, VOCs and particle levels were measured from 29 May to 26 June, 2013 (28 days) and O₃ 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

(100 m² in this case). The extent of ground vegetation (shrubs, bushes, meadow vegetation) was estimated visually at both tree-covered and open areas and classified into dense, intermediate and meager (Table 1).

The degree of canopy closure was $84.7\% \pm 8.0$ (mean $\pm$ SD) in the tree-covered sampling sites. The total number of trees recorded was 73.7 ± 45.5 , with large trees (DBH > 32 cm) comprising 4.4% (± 5.1) of all the trees. The sampling sites were dominated by deciduous trees ($96\% \pm 7$), including forest tree species (*Betula* spp. and *Sorbus aucuparia* being dominant with scattered *Populus* spp. and *Prunus padus*) typical to Southern Finland. Traffic flow data (monthly average, Table 1) were obtained from the City of Helsinki (2012) and the Finnish Transport Agency (2010). Mean annual anthropogenic pollution concentrations, measured at several sampling locations in Helsinki in 2013, were 14–49 $\mu\text{g m}^{-3}$ for NO₂, 39–52 $\mu\text{g m}^{-3}$ for O₃, 2–6 $\mu\text{g m}^{-3}$ for AVOCs (benzene, toluene and xylenes combined) and 11–25 $\mu\text{g m}^{-3}$ for PM₁₀ (Air quality in Finland, 2015). Mean annual NO₂, O₃ and PM₁₀ concentrations at municipal monitoring stations do not usually exceed annual human health limit values of 40 $\mu\text{g m}^{-3}$, 120 $\mu\text{g m}^{-3}$ and 40 $\mu\text{g m}^{-3}$, respectively, with the exception of NO₂ in a few highly trafficked locations. Regarding AVOCs, an annual threshold value is available only for benzene (5 $\mu\text{g m}^{-3}$). For BVOCs no threshold values are available. A wind rose showing the prevailing wind direction and speed during the measuring periods is shown in Fig. 2. The monthly average temperature in Helsinki in June 2013 was 18.1 °C and in June 2014 13.6 °C, representing typical temperatures in June in the Helsinki area.

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 log₁₀ 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 ($\pm$ 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 (NO₂, 2.6% higher in tree-covered areas, *p* = 0.407; O₃, 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

277
278 Results from our study, conducted under northern summertime conditions (June), suggest that
279 forest vegetation in near-road urban environments does not improve local air quality in terms of
280 gaseous (NO_2 , O_3 , AVOCs) air pollutants, thus corroborating earlier findings in late summer
281 (August-September) in two Finnish cities (Setälä et al., 2013). In a similar study in Sweden, but
282 only from one measurement site, Grundström and Pleijel (2014) found slightly (7%) reduced
283 NO_2 concentrations in the forest canopy. However, besides the canopy effect, this reduction may
284 have resulted from the 4 m difference in distance between their open and canopy sampling points
285 from a heavy traffic road (the latter being further away from the road) (see e.g. HSY, 2014). In
286 the same study, the authors did not detect reduced O_3 concentrations in the canopy (Grundström
287 & Pleijel, 2014), which is in line with our results. Fantozzi, Monaci, Blanus & Bargagli (2015)
288 found lower NO_2 concentrations under the canopies of Mediterranean trees (evergreen *Quercus*
289 *ilex* L.) growing 1-10 m from a road compared to a nearby open-field transect. However, reduced
290 O_3 concentrations in the canopy were observed only during post-summer rainfalls (Fantozzi et al.
291 2015), indicating that the impact of vegetation on gaseous pollution concentrations may also
292 depend on the type of local vegetation and climatic conditions. On the other hand, Harris and
293 Manning (2010) found, also using passive samplers, higher NO_2 and lower O_3 levels within
294 urban tree canopies than outside them. They suggested that this results from NO_x/O_3 chemistry
295 related to gas interactions between soil and the air, as described by Fowler (2002). Although the
296 three gases in our study were sampled at the same locations, O_3 was collected a year later than
297 NO_2 and VOC preventing us from comparing NO_2 and VOC levels directly with those of O_3 .
298 Furthermore, using data collected during one month only to unravel complex interactions

between NO₂, O₃ 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

methodology in this study, it should be noted that particles that can enter throughout the human respiratory system are smaller than 2.5 μm in diameter, and these are easily outweighed by larger particles.

Sampling in the current study was done in June, i.e. during midsummer in Finland when total leaf area, as well as gas exchange between leaves and ambient air, is high (Rautiainen, Heiskanen & Korhonen, 2012). However, when comparing our results to Setälä et al. (2013), in which sampling took place in late summer (from early August to early September) when leaf activity is ceasing, it is interesting to note that road-side vegetation did not reduce NO_2 and AVOC concentrations neither during mid- nor late summer seasons. In order to explore the canopy effect for the entire growth period, the duration of measuring campaigns during the same year should extend over the entire leaf period.

Estimates on the ability of trees to absorb anthropogenic VOCs are based on a few laboratory incubation studies (Cornejo, Munoz, Ma & Stewart, 1999; Keymeulen et al., 1995; Yang, Pennisi, Son & Kays, 2009). To our knowledge, the fate of AVOCs in relation to urban vegetation has only been investigated in one study in Las Vegas, U.S. (Hiatt, 1998), where samples of air and leaves of several tree species were analyzed. Hiatt (1998) showed that several local tree species can absorb AVOCs according to existing models. However, our results indicate that the potential of trees to create areas of lower AVOC concentrations at the local scale in northern climates is meager, at least in urbanized sites where deciduous trees constitute most of the vegetation, corroborating Setälä et al. (2013).

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 NO₂, O₃ 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

have been needed to tackle this variation. Nevertheless, the reduction in particle levels is best explained by either effective deposition of large (and heavy) particles on vegetation surfaces or perhaps - more importantly - by reduced ventilation under the canopy. Wind speed is known to be lower under thick canopies compared to open, treeless areas (Belcher et al., 2012; Setälä et al., 2013; Wania, Bruse, Blond & Weber, 2012), which likely prevents road dust from dispersing further away from the road in tree-covered areas.

Due to the fact that air pollution patterns can be shaped by wind conditions in urban areas (Choi, He, Barbesant, Kozawa, Mara, Winer & Paulson, 2012; Kozawa, Winer & Fruin, 2012; McNabola, Broderick & Gill, 2009), the placement of sampling devices in relation to prevailing wind patterns deserved attention in our study set-up. As the prevailing wind direction (long-term average) in June in Helsinki is from the south or south-west, all sampling sites were placed downwind from the pollution source. Wind direction, however, varied considerably during the one-month measuring periods in 2013 and 2014 and no clear consistency in wind direction at the study region was evident (Fig. 2). However, south-western and eastern winds dominated, and only a small percentage of winds blew from the north in June 2013. Thus, for most of that campaign period, our sampling units were downwind or at least in a neutral position, but clearly not upwind, in relation to pollution sources. In June 2014, when O₃ was measured, winds blew from almost all directions. Moreover, the relatively long sampling period used is bound to diminish the impacts of short-term wind direction changes and local eddies on our results. The concentrations of NO₂, O₃ and AVOCs were in line with the available mean annual and monthly (June 2013) concentration data from Helsinki, and always below the limit values for human 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.

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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 NO₂, O₃, 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.	<i>R</i>	0.023	0.484	0.090	0.036	0.138	0.024
	<i>p</i>	0.950	0.157	0.804	0.921	0.704	0.920
NO ₂	<i>R</i>	—	—	—	—	0.130	0.787
	<i>p</i>	—	—	—	—	0.720	<0.001
O ₃	<i>R</i>	—	—	—	—	0.074	0.545
	<i>p</i>	—	—	—	—	0.839	0.013
T-AVOC	<i>R</i>	—	—	—	—	0.169	0.207
	<i>p</i>	—	—	—	—	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 %
<i>m/p</i> -xylene	22 %
Styrene	2.3 %
Ethyl <i>tert</i> -butyl ether	0.9 %
Propylbenzene	1.6 %
2-Ethyltoluene	2.9 %
3-Ethyltoluene	5.2 %
4-Ethyltoluene	1.8 %
BVOC	
α -pinene	47 %
β -pinene	13 %
d-carene	13 %
limonene	26 %

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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).

Fig. 3. Concentrations of (a) NO₂, (b) O₃, (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 $\pm$ 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.