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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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24 Abstract

25 The ability of urban vegetation to improve air quality for the benefit of urban residents is often
26 considered fact since plants can absorb and capture air pollutants. However, there is little
27 empirical evidence that urban air quality at the local scale is improved by the presence of, e.g.
28 trees, especially in northern climatic regions. We studied the impact of urban forest vegetation
29 on the levels of five types of air pollutants (NO₂, ground-level O₃, anthropogenic and biogenic
30 VOCs, and particulate matter) in near-road environments during summer (June) using passive
31 samplers in Helsinki, Finland. Concentrations of gaseous pollutants did not differ significantly
32 between tree-covered and adjacent open areas, while particle pollutant levels were significantly
33 lower in tree-covered areas than in adjacent open, treeless areas. Vegetation-related variables
34 (canopy closure, tree number and size, and ground vegetation) did not explain differences in air
35 quality. Our results suggest that the role of urban, mostly deciduous, vegetation is negligible in
36 improving local air quality, in terms of the anthropogenic pollutants measured here, in northern
37 climates. However, air particulate pollution, which is likely to be dominated by large-sized
38 particles in our study, can be reduced by urban vegetation.

39

40 Highlights:

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

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47 **1. Introduction**

48

49 Poor air quality due to air pollutants is amongst the most recognized environmental problems in
50 urbanized areas around the world. In Europe, the levels of air pollutants have generally
51 decreased within the past decades, but in many urban areas the levels of particulate matter,
52 nitrogen dioxide (NO₂), ground-level ozone (O₃), and anthropogenic volatile organic compounds
53 (AVOC) are still high enough to cause severe risk to human health (EEA, 2014). Most of these
54 air pollutants originate from energy production and road traffic (EEA, 2014).

55

56 Although reducing air pollutant emissions is likely to be the most effective way to improve air
57 quality (EEA, 2014), it is widely believed that vegetation – due to its ability to absorb and
58 capture air pollutants with its large leaf area – can be used to mitigate urban air pollution
59 problems (Beckett, Freer-Smith & Taylor, 2000a; Nowak, 2006; Nowak, Crane & Stevens,
60 2006). For example, trees and herbaceous plants capture particulate pollution by dry deposition
61 on their large leaf surfaces (Hofman, Stokkaer, Snauwaert & Samson, 2013; Räsänen,
62 Holopainen, Joutsensaari, Ndam, Pasanen, Rinnan & Kivimäenpää, 2013; Weber, Kowarik &
63 Säumel, 2014).

64

65 Furthermore, trees and other vegetation can absorb gaseous air pollutants, mainly from air to
66 leaf, where gases such as NO₂ (Chaparro-Suarez, Meixner & Kesselmeier, 2011; Rondón &
67 Granat, 1994; Takahashi, Higaki, Nohno, Kamada, Okamura, Matsui, Kitani & Morikawa,
68 2005), O₃ (Harris & Manning, 2010; Manes, Incerti, Salvatori, Vitale, Ricotta & Costanza, 2012;
69 Wang, Zhou, Wang, Gao, Zheng, Tong & Ouyang, 2012) and anthropogenic volatile organic

70 compounds (AVOC) (Doty, James, Moore, Vajzovic, Singleton, Ma, Khan, Xin, Kang, Park,
71 Meilan, Strauss, Wilkerson, Farin & Strand, 2007; Keymeulen, Schamp & Van Langenhove,
72 1995) are absorbed through the stomata into the leaf interior. Consequently, the mitigation of air
73 pollution is often considered an important ecosystem service provided by urban vegetation (e.g.
74 Chaparro & Terradas, 2009; Jim & Chen, 2008; Manes et al., 2012; Nowak, Crane, Stevens,
75 Hoehn, Walton & Bond, 2008).

76

77 Forests and other vegetation in rural and urban areas emit biogenic volatile organic compounds
78 (BVOC) while human activities produce AVOCs, which, together with NO_x ($\text{NO} + \text{NO}_2$), play a
79 key role in the formation of ozone (O_3) in the tropospheric air (Calfapietra, Fares, Manes,
80 Morani, Sgrigna & Loreto, 2013; Loreto & Schnitzler, 2010). Under VOC-limited conditions,
81 ground-level O_3 levels are usually lower in urban (high NO_x levels) than in rural areas with NO_x -
82 limited conditions (low NO_x levels, but higher BVOC levels) (Calfapietra et al., 2013; EEA,
83 2014). However, in recent years, O_3 levels in European and North American cities have
84 increased more than in rural sites, although peak values are decreasing in both environments
85 (Paoletti, De Marco, Beddows, Harrison & Manning, 2014).

86

87 Despite the wealth of studies suggesting that urban vegetation is able to purify air for the benefit
88 of urban inhabitants, contradictory results and comments have emerged recently (Gromke &
89 Ruck, 2009; Harris & Manning, 2010; Pataki, Carreiro, Cherrier, Grulke, Jennings, Pincetl,
90 Pouyat, Whitlow & Zipperer, 2011; Pataki, Alberti, Cadenasso, Felson, McDonnell, Pincetl,
91 Pouyat, Setälä & Whitlow, 2013; Vos, Maiheu, Vankerkom & Janssen, 2013). Critique is based
92 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, Hirabayashi & 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 NO₂
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

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

125

126 **2. Methods**

127

128 *2.1. Sampling methods*

129

130 We measured air pollutant levels using dry deposition passive samplers, placed either under tree
131 canopies in tree-covered areas or in adjacent treeless open areas in near-road environments in the
132 Helsinki Metropolitan Area (60°10'15"N, 24°56'15"E), southern Finland (Fig. 1). The air
133 pollutants measured were i) nitrogen dioxide (NO₂), ii) ground-level ozone (O₃), iii) a selection
134 of typical anthropogenic volatile organic compounds (AVOCs), iv) biogenic volatile organic
135 compounds (BVOCs), which is a selection of the most common monoterpenes in Finnish forests
136 alongside isoprenes (Lindfors & Laurila, 2000), and v) particulate matter. For NO₂ and O₃ we
137 used diffusive samplers developed by the Swedish Environmental Research Institute IVL, where
138 the gas is adsorbed to a filter paper inside the collector and the amount of gas is analyzed by

139 extracting it from the filter to distilled water, after which the amount of gas is determined with a
140 spectrophotometer (Ferm & Svanberg, 1998). AVOCs and BVOCs (see Table 3 for the list of
141 compounds) were sampled using diffusive Carbopack B adsorbent tubes and analyzed according
142 to the EN ISO 16017-2 standard, where the concentrations of the studied compounds, counted
143 from individual adsorbent tubes, are determined by comparing them to compound-specific
144 standard substances. VOC results are presented as total AVOCs (= T-AVOCs, including all the
145 sampled AVOC compounds) and as total BVOCs (= T-BVOCs, including all the sampled BVOC
146 compounds). Particle pollution levels were measured using passive collectors developed by IVL
147 (Ferm, Watt, O'Hanlon, De Santis & Varotsos, 2006). NO₂ samplers and their analyses were
148 provided by Metropolilab, Helsinki, Finland, O₃ and particle samplers and their analyses by IVL,
149 and VOC samplers and their analyses by Ramboll Analytics, Lahti, Finland.

150

151 The sampling of NO₂, O₃ and VOCs is based on molecular diffusion. The method has some
152 limitations, but has been successfully used in numerous studies, with results strongly in line with
153 continuous air monitoring (Ayers, Keywood, Gillett, Manins, Malfroy & Bardsley, 1998; HSY,
154 2014; Krupa & Legge, 2000). The passive particle sampling method is based on the deposition of
155 particles by impaction and diffusion on a vertically-mounted cylindrical Teflon surrogate
156 surface. The method does not provide information on the specific particle size fractions, but
157 provides the mass of deposited particles on the sampler surface. Mass is calculated by weighing
158 the surrogate surface before and after exposure. The surrogate surfaces are equilibrated for 24 h
159 before weighing in a weighing room at 20°C and 50% relative humidity (Ferm et al., 2006).
160 Ferm et al. (2006) noted that particle deposition on Teflon correlated well with PM₁₀
161 concentrations when samplers were not situated in the immediate vicinity of roads.

162

163 *2.2. Sampling sites and dates*

164

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

179

180 The samplers were mounted under rain shields fixed to 40 cm-long aluminium L-shaped sampler
181 holders (together forming a sampling unit), which were attached to lamp posts or wooden poles
182 in the open areas. In the tree-covered areas the sampler holders were attached to tree trunks
183 directly under the canopy. The shields and sampler holders were manufactured by IVL. The
184 sampling units for NO₂, VOCs and particles were mounted 2.0-3.5 m above ground depending

185 on a suitable mounting structure. O₃ sampling units were mounted 3.2 m above ground to
186 prevent them from being too close to the ground where O₃ gets depleted (Mills, Pleijel, Bükér,
187 Braun, Emberson, Harmens, Hayes, Simpson, Grünhage, Karlsson, Danielsson, Bermejo &
188 Gonzalez Fernandez, 2010). Within each site, the sampling units (open and tree-covered) were
189 always placed at the same distance from the side of the road (a line marking the outer boundary
190 of the road). At different sites, depending on the availability of suitable mounting structures, the
191 sampling unit pairs were situated at slightly different distances from the road side; ranging
192 between 18 and 30 m (mean = 25.6 m). The forest edge in tree-covered areas was, on average,
193 6.2 m (0 – 14 m) from the road side. The area between the road and the forest edge was open
194 with short grass or meadow vegetation. Measurements were carried out during midsummer when
195 plant leaves were fully developed: NO₂, VOCs and particle levels were measured from 29 May
196 to 26 June, 2013 (28 days) and O₃ was measured from 2 June to 7 July, 2014 (35 days).

197

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

208 (100 m² 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 $84.7\% \pm 8.0$ (mean \pm 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 ($96\% \pm 7$),
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 $\mu\text{g m}^{-3}$ for NO₂, 39–52 $\mu\text{g m}^{-3}$ for O₃, 2–6 $\mu\text{g m}^{-3}$ for
220 AVOCs (benzene, toluene and xylenes combined) and 11–25 $\mu\text{g m}^{-3}$ for PM₁₀ (Air quality in
221 Finland, 2015). Mean annual NO₂, O₃ and PM₁₀ concentrations at municipal monitoring stations
222 do not usually exceed annual human health limit values of 40 $\mu\text{g m}^{-3}$, 120 $\mu\text{g m}^{-3}$ and 40 $\mu\text{g m}^{-3}$,
223 respectively, with the exception of NO₂ in a few highly trafficked locations. Regarding AVOCs,
224 an annual threshold value is available only for benzene (5 $\mu\text{g m}^{-3}$). 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*

231

232 We analyzed the air pollution data using paired samples *t*-test to determine if there is a difference
233 in pollution levels between the tree-covered and open study areas. We considered *p*-values <
234 0.05 to indicate statistically significant differences between treatments. Data were \log_{10}
235 transformed to stabilize the variance of individual properties where necessary. Linear regression
236 was applied to detect possible correlations between measured environmental variables and
237 pollution level differences between the tree-covered and open areas. In open areas, the influence
238 of ground vegetation on air pollution was tested using the pollution levels of open areas. T-
239 BVOCs were not tested because BVOCs are emitted mainly by trees and not by shrubs and other
240 typical grassland vegetation. The impact of traffic flow on pollution levels was tested using the
241 actual pollutant levels measured at each sampling point, including both open and tree-covered
242 areas. T-BVOCs were not tested because BVOCs are not traffic-emitted substances. Statistical
243 analyses were performed using SPSS Statistics, version 21.

244

245 **3. Results**

246

247 Results for each air pollutant are presented both as means (\pm SD) of all sites (tree-covered vs.
248 open area comparisons), and for each site separately along the traffic flow gradient (number of
249 motor vehicles day⁻¹) to explore a potential correlation between pollutant levels and traffic flow
250 (Fig. 3). As for total BVOCs (T-BVOCs), values are presented in relation to % canopy closure to
251 depict the association between increasing canopy closure and T-BVOC levels (Fig. 3).
252 Concentrations of the gaseous pollutants did not differ significantly between tree-covered and
253 open areas (NO₂, 2.6% higher in tree-covered areas, *p* = 0.407; O₃, 3.8% lower in tree-covered

254 areas, $p = 0.177$; total AVOC (T-AVOC), 2.7% lower in tree-covered areas, $p = 0.718$; T-BVOC,
255 9.5% higher in tree-covered areas, $p = 0.432$) (Fig. 3a-d). Thus, tree-cover had no effect on the
256 concentrations of gaseous pollutants, while traffic flow explained most of the variation in NO₂
257 concentrations and some of the variation in O₃ concentrations between sites (Table 2). For T-
258 AVOCs and particle levels, no such correlation was evident, neither in tree-covered nor in open
259 areas (Table 2). A detailed listing of the constituent AVOCs and BVOCs and their proportions
260 are shown in Table 3. The proportions of AVOC and BVOC constituents were insensitive to the
261 presence of trees (results not shown).

262
263 In contrast to gaseous pollutants, particle pollution levels differed statistically significantly
264 between the tree-covered and open study areas: particle levels were, on average, 23% ($p = 0.023$)
265 lower in tree-covered areas than in open areas (Fig. 3e). None of the measured vegetation
266 properties correlated statistically significantly with the difference in particle levels between the
267 tree-covered and open areas (Table 2). As NO₂, O₃, T-AVOC and T-BVOC concentrations did
268 not differ statistically significantly between tree-covered and open areas, the relationships
269 between their differences and vegetation properties could not be tested.

270
271 None of the vegetation properties measured in the tree-covered areas correlated statistically
272 significantly with T-BVOC levels (results not shown), although there appears to be a trend in T-
273 BVOC levels for total number of trees ($R = 0.616$, $p = 0.078$) and % canopy closure ($R = 0.546$,
274 $p = 0.129$).

275

276 **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 (NO₂, O₃, 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 NO₂ 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 O₃ concentrations in the canopy (Grundström
287 & Pleijel, 2014), which is in line with our results. Fantozzi, Monaci, Blanusa & Bargagli (2015)
288 found lower NO₂ 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 O₃ 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 NO₂ and lower O₃ levels within
294 urban tree canopies than outside them. They suggested that this results from NO_x/O₃ 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, O₃ was collected a year later than
297 NO₂ and VOC preventing us from comparing NO₂ and VOC levels directly with those of O₃.
298 Furthermore, using data collected during one month only to unravel complex interactions

299 between NO₂, O₃ and VOCs is challenging due to the rapid and complex dynamics of these
300 compounds in the air.

301

302 Our results, however, do support earlier studies showing that trees can mitigate problems
303 associated with particulate air pollution (e.g. Beckett et al., 2000a,b; Cavanagh et al., 2009;
304 Tallis, Taylor, Sinnett & Freer-Smith, 2011), particularly in the near-road environment (Baldauf,
305 Thoma, Khlystov, Isakov, Bowker, Long & Snow, 2008; Islam, Rahman, Bahar, Habib, Ando &
306 Hattori, 2012; Maher, Ahmed, Davison, Karloukovski & Clarke, 2013; Setälä et al., 2013;
307 Steffens, Wang & Zhang, 2012), although the tree effect can depend on environmental
308 conditions such as wind direction in relation to pollution source, as well as particle size (Brantley
309 et al., 2014; Hagler, Lin, Khlystov, Baldauf, Isakov, Faircloth & Jackson, 2012; Tong, Whitlow,
310 MacRae, Landers & Harada, 2015). Although the method used in our study does not allow for
311 the measurement of size fractions of the collected particles, it is likely that coarse particles, most
312 likely road dust, were emphasized in the mass deposition (Ferm et al., 2006); the Teflon
313 sampling surfaces were visibly dirtier close to the road than further away. However, regarding
314 smaller particles, the situation can be different: Tong et al. (2015) investigated the dispersion of
315 particulates near roads using aerosol spectrometers in brief monitoring campaigns and found that
316 PM_{2.5} concentrations were higher along a transect with trees downwind from the road and
317 declined less sharply than along open transects without trees. Also, as noted by Setälä et al.
318 (2013), particle levels, measured with passive samplers, were notably and significantly lower in
319 tree-covered areas compared to open areas, but often inconsistent with particle data gathered
320 using “active” collecting devices, which can specify particle size fractions and produce results
321 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

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

352
353 That concentrations of gaseous pollutants appeared to be unresponsive to forest vegetation, while
354 particle pollution levels were clearly reduced by tree-cover, can be due to the inefficiency of
355 northern vegetation to absorb and process gaseous pollutants, such as NO₂, O₃ and AVOCs. The
356 amount of pollutants absorbed by stomatal intake seems to be irrelevant in the context of ambient
357 concentrations. However, even if the vegetation could absorb these pollutants efficiently, it is
358 possible that reduced air flow within tree-covered sites (Belcher, Harman & Finnigan, 2012;
359 Gromke & Ruck, 2009; Wuyts, Verheyen, De Schrijver, Cornelis & Gabriels, 2008) can increase
360 pollutant levels within the canopy and thus have negative impacts on local air quality (see Setälä
361 et al., 2013; Viippola et al., 2016; Vos et al., 2013), while in open areas the polluted air mass is
362 mixed by wind and diluted more rapidly. Such an indirect effect of vegetation on local air quality
363 is seldom reported in the literature and merits more research.

364
365 The clear reduction in particle levels at tree-covered sites did not relate to any of the measured
366 vegetation properties. It is possible that the vegetation parameters measured here were not
367 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 O₃ 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 NO₂, O₃ 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).

391

392 5. Conclusions

393

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

406

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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 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	
a-pinene	47 %
b-pinene	13 %
d-carene	13 %
limonene	26 %

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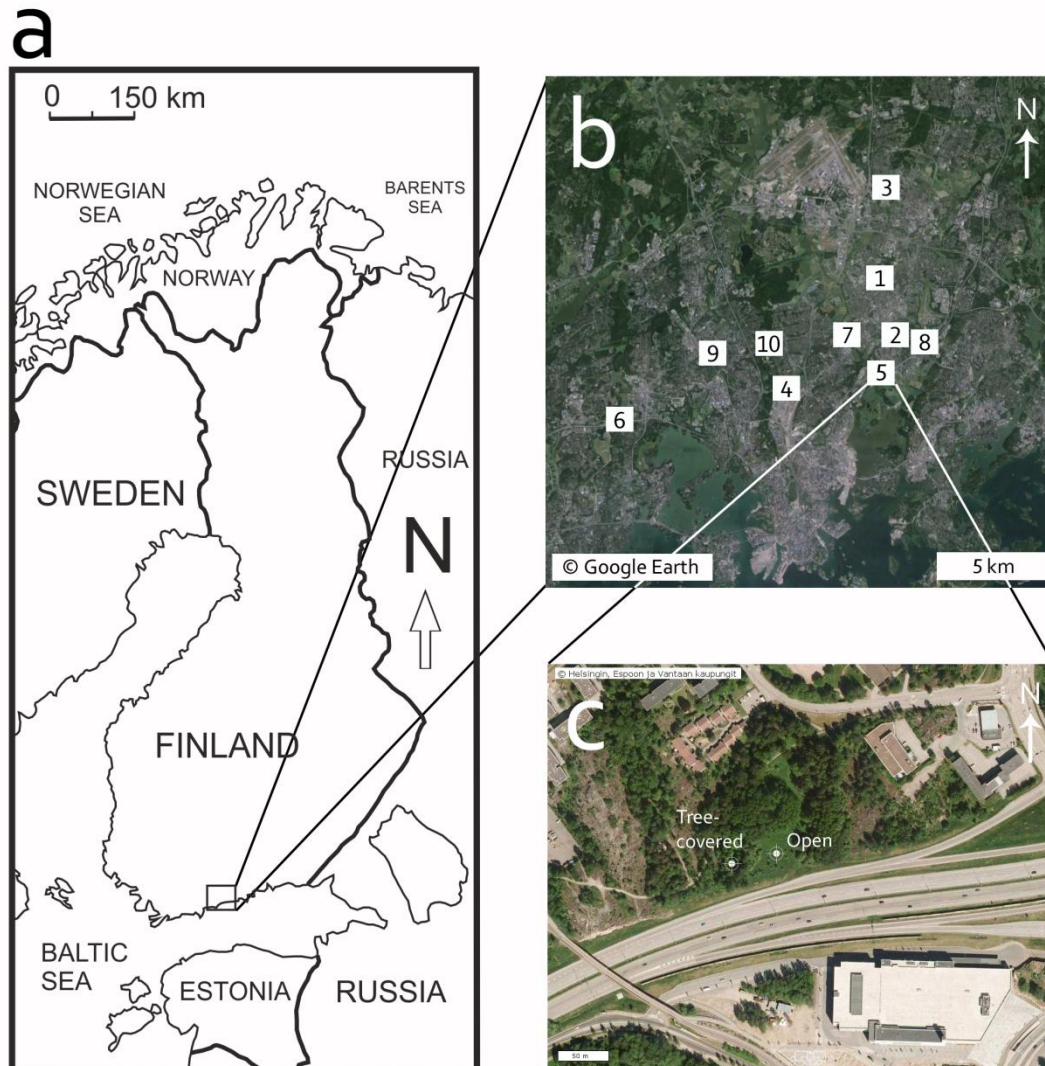


Fig. 1. (a) A map of Finland with (b) an aerial image of the Helsinki Metropolitan Area displaying locations of the ten sampling sites (1 – 10), and (c) an aerial image of one of the sampling sites (site 5) as an example. At each of the 10 sites, air quality was measured in one tree-covered and one open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

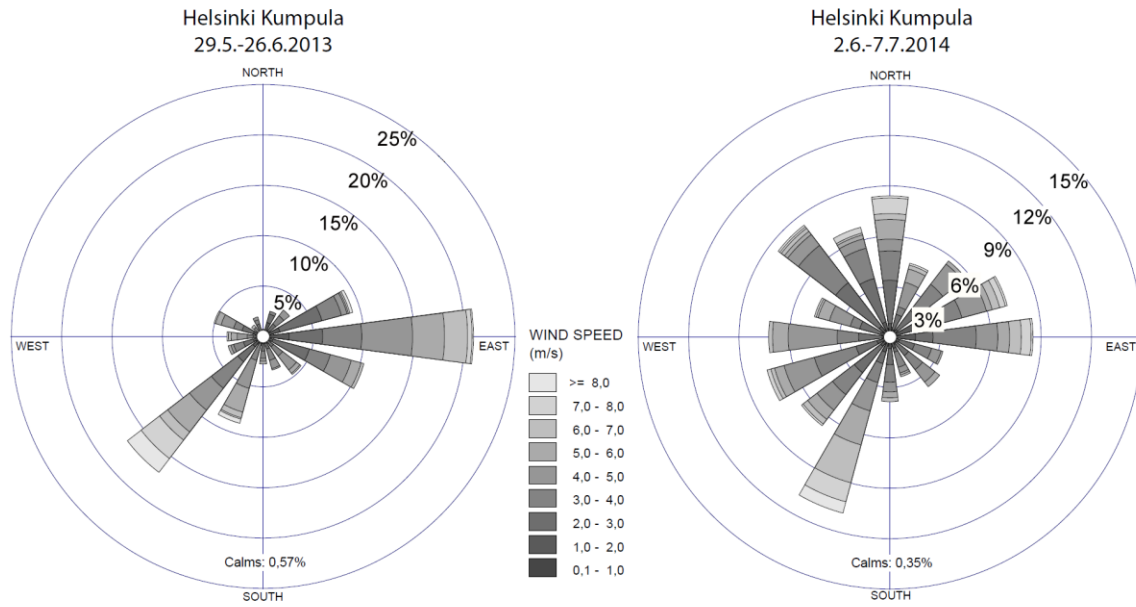


Fig. 2. Wind direction and speed during 29 May – 26 June, 2013 and 2 June – 7 July, 2014 in Helsinki (Kumpula measuring station). Data were provided by the Finnish Meteorological Institute (FMI).

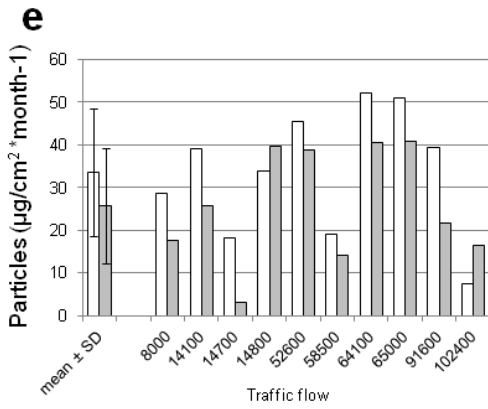
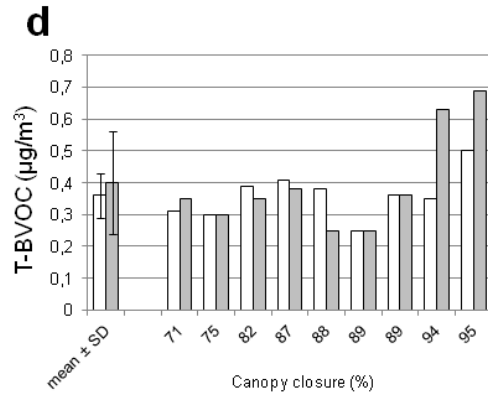
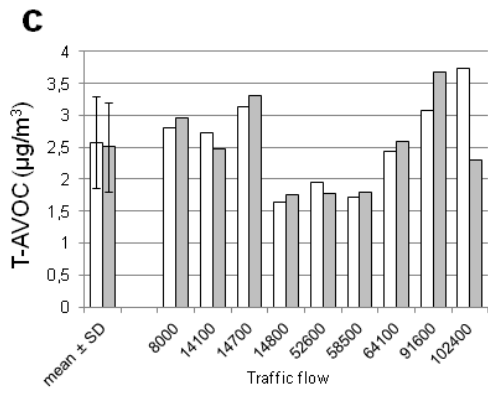
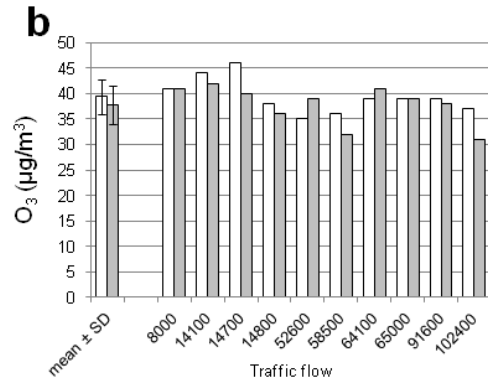
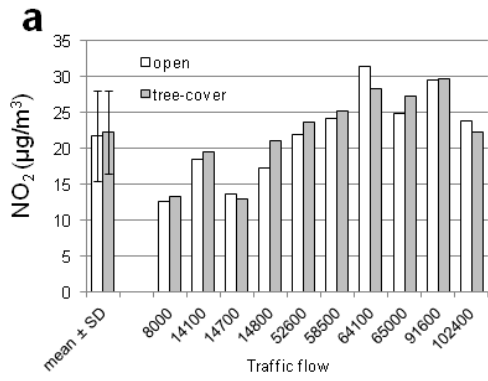


Fig. 3. Concentrations of (a) NO₂, (b) O₃, (c) total AVOCs, (d) total BVOCs and (e) levels of particles (mass of airborne particles deposited on the sampler) in open (white bars) and tree-covered (grey bars) areas. The first pair of bars in each panel refers to mean \pm SD ($n = 10$, except for total 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.