Greenbelts do not reduce NO_2 concentrations in near-road environments

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Abstract

Trees are believed to improve air quality, thus providing an important ecosystem service for urban inhabitants. However, empirical evidence on the beneficial effects of urban vegetation on air quality at the local level and in boreal climatic regions is scarce. We studied the influence of greenbelt-type forest patches on NO_2 levels (i) in front of, (ii) inside and (iii) behind greenbelts next to major roads in the Helsinki Metropolitan Area, Finland, during summer and winter using passive collectors. Concentrations of NO_2 were significantly higher in front of greenbelts compared to road sides without greenbelts. The more trees there were inside greenbelts the higher the NO_2 level in front of greenbelts, likely due to the formation of a recirculation zone of air flow in front of greenbelts. Similarly, NO_2 levels were higher inside greenbelts than in open areas without them, likely due to reduced air flow inside greenbelts. NO_2 levels behind greenbelts were similar to those detected at the same distance from the road but without greenbelts. Our results suggest that, regardless of season, roadside greenbelts of mostly broadleaf trees do not reduce NO_2 levels in near-road environments, but can result in higher NO_2 levels in front of and inside greenbelts.

Keywords: air pollution, urban vegetation, ecosystem services, vegetation barrier, passive samplers, urban trees

Highlights:

- NO_2 levels were higher in front of and inside greenbelts than in nearby open areas
- NO_2 levels were not lower behind greenbelts than in open areas without greenbelts
- Denser greenbelts increased NO_2 concentrations between roads and greenbelts
- Reduced air flow in front of and inside greenbelts resulted in higher NO_2 levels
- NO_2 levels behind greenbelts did not decrease due to a greenbelt-induced windbreak

1. Introduction

Air pollution is one of the most severe environmental problems in urbanized areas around the world. Although levels of certain air pollutants have decreased during recent decades, concentrations of, e.g. nitrogen dioxide (NO_2) are still too high in many urban areas from a human and ecosystem health perspective (Duncan et al., 2016; EEA, 2016). NO_2 mainly originates from energy production, industry and road traffic (EEA, 2016). In urban areas, road traffic can be the main emitter of nitrogen oxides ($NO_x = NO + NO_2$) as NO, which is quickly oxidized by O_3 to NO_2, or directly as NO_2 (Anttila et al., 2011). High NO_2 concentrations can increase respiratory symptoms and infections especially with asthmatic individuals and children (Kampa & Castanas, 2008) and lead to an increased prevalence of atopic sensitizations, allergic symptoms, and diseases (Krämer et al., 2000).

Although the key action to improve air quality should be the reduction of air pollutant emissions (EEA, 2016), it has been widely suggested that vegetation, which captures air pollutants with its large leaf area, can be effectively used to clean polluted urban air (Beckett et al., 2000; Nowak, 2006; Nowak et al., 2006). For example, gases such as NO_2 (Chaparro-Suarez et al., 2011; Rondón & Granat, 1994; Takahashi et al., 2005) are absorbed from the air through the stomata into the leaf interior of a plant. Such air purification provided by urban vegetation is often considered an important ecosystem service (e.g. Jim & Chen, 2008; Manes et al., 2012; Nowak et al., 2008), especially when the data are based on model interpretations, which often refer to city-scale ambient air quality improvement (e.g. Baumgardner et al., 2012; Hirabayashi et al., 2012; Morani et al., 2011; Nowak et al., 2013; Selmi et al., 2016).

However, the relevance of this ecosystem service has recently been challenged by critical comments and contradictory results from local-scale studies (Gromke & Ruck, 2009; Harris & Manning, 2010; Pataki et al., 2011; Pataki et al., 2013; Vos et al., 2013). Studies in which pollutant concentrations have been measured locally, e.g. in a forest or park and compared to concentrations in adjacent open, treeless areas, have been scarce. However, an increasing number of such studies, especially those performed in near-road environments, have been published (Brantley et al., 2014; Fantozzi et al., 2015; Harris & Manning, 2010; Setälä et al., 2013; Tong et al., 2015; Viippola et al., 2016; Yin et al., 2011; Yli-Pelkonen et al., 2017). For example, Setälä et al. (2013) and Yli-Pelkonen et al. (2017) observed no significant differences in gaseous pollutant concentrations between tree-covered urban parks or remnant forests and open areas in near-road environments in hemi-boreal climatic conditions, while Viippola et al. (2016) found higher PAH concentrations under tree canopies than in nearby open areas close to roads in Finland.

Greenbelts are elongated tree plantations or forest patches forming fence-like vegetation barriers along roads (see Fig. 1; Gallagher et al., 2015). Greenbelts have been suggested to filter air pollutants and prevent them from spreading from the road, as well as alter air flow patterns that results in cleaner air behind them (Hagler et al., 2012; Islam et al., 2012; Maher et al., 2013). However, air pollutant levels between roads and greenbelts (Al-Dabbous & Kumar, 2014; Tong et al., 2016) or solid barriers (Baldauf et al., 2008; Hagler et al., 2011) can be elevated due to the formation of a recirculation zone of air. The impacts of greenbelt structures depend on the design of the planting type and species configuration (Chen et al., 2016; Steffens et al., 2012; Tong et al., 2016). A majority of these studies have focused on particulate matter, such as ultrafine particles (UFP), while only a few have concentrated on gaseous air pollutants, mainly CO (Baldauf et al., 2008; Hagler et al., 2012; Sulistyantara et al., 2016).

The aim of our study was to explore the capacity of urban greenbelts to remove the traffic-derived gaseous pollutant NO_2 under summertime and wintertime conditions in Finland. We hypothesized that (1) NO_2 concentrations in front of greenbelts are higher than those measured at the same distance from the roads, but without greenbelts. We also expected that (2) NO_2 concentrations inside greenbelts are slightly lower or do not differ from those measured at the same distances from the road in open areas. Further, we hypothesized that (3) NO_2 concentrations behind greenbelts are lower compared to those measured in open areas without greenbelts. Finally, we expected that (4) the impact of vegetation on NO_2 concentrations in front of, inside and behind the greenbelts relates to vegetation properties of the greenbelt.

2. Materials and methods

2.1. Sampling

We measured NO_2 concentrations using dry deposition passive collectors in near-road environments in the Helsinki Metropolitan Area (60°10′15″N, 24°56′15″E), southern Finland (Fig. 1). We used diffusive collectors developed by the Swedish Environmental Research Institute IVL, where gas is adsorbed to a filter paper inside the collector. After collection, the sampler filters were extracted in 5 ml HPLC-grade water in sealed plastic bags (Ayers et al., 1998). To determine the amount of NO_2, the filter extracts were analyzed with a spectrophotometer (λ = 540 nm), after mixing with a diazotizing reagent (Ayers et al., 1998). According to Ferm & Rodhe (1997), the estimated measuring range for IVL-type NO_2 passive samplers is approximately 0.05-200 ppbv for a two-month sampling period. NO_2 collectors and their analyses were provided by Metropolilab, Helsinki, Finland. The method has some limitations but has been successfully used in numerous studies. According to previous studies, IVL-type NO_2 passive samplers have been very reliable and concentrations obtained from the passive samplers have shown a strong correlation with those measured using continuous NO_2 monitoring instruments (Ayers et al., 1998; Ferm & Rodhe, 1997; Kaski et al., 2016; Klingberg et al., 2017; Krupa & Legge, 2000; Loukkola et al., 2004) and thus single sets of samplers were used in this study.

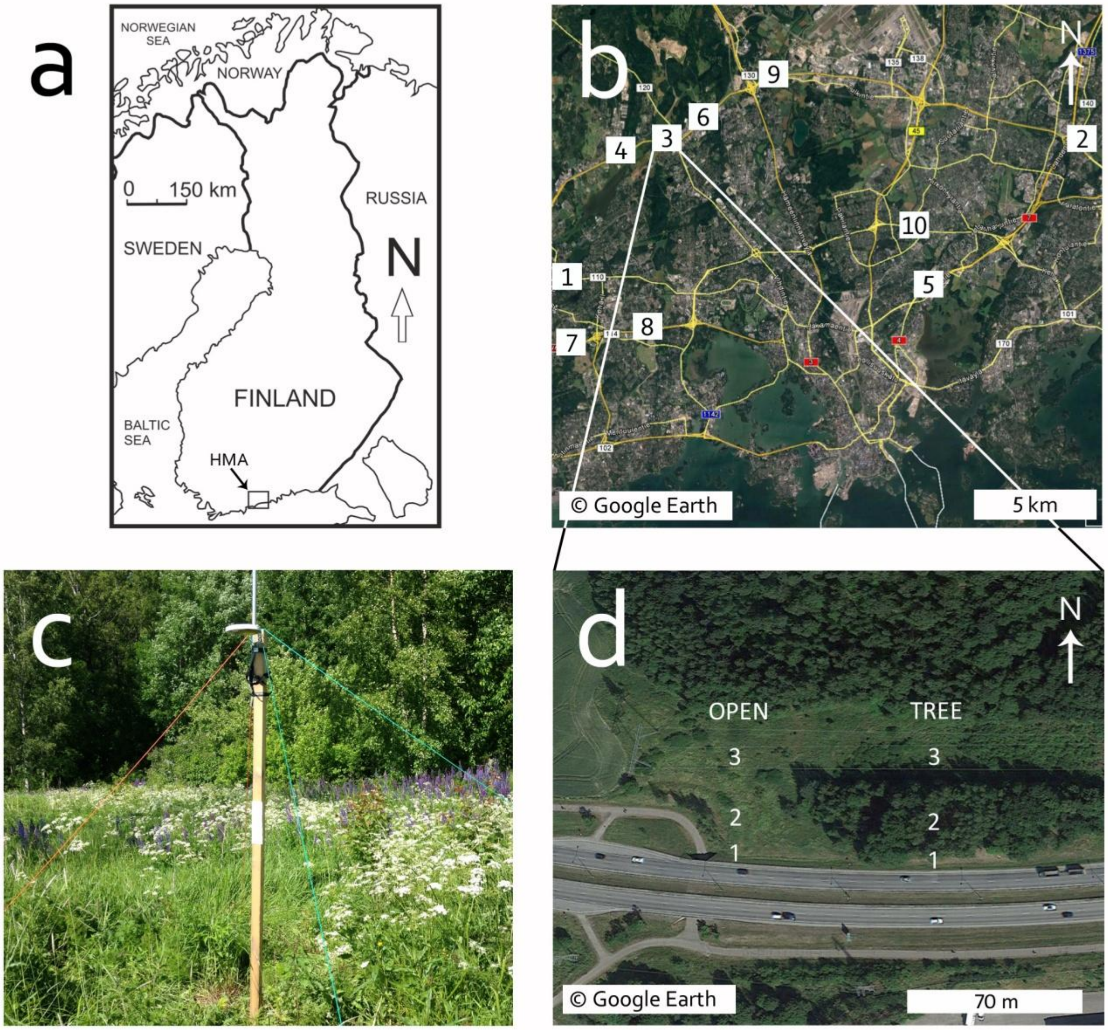


Fig. 1. Locations of the ten sampling sites. Panel (a) presents the location of the Helsinki Metropolitan Area (HMA) in Finland, panel (b) shows locations of the ten sampling sites in the area (major roads are shown in yellow), panel (c) displays the NO_2 passive collector setup under a rain shield attached to a wooden pole in an open area, and panel (d) displays an example of one of the sampling sites (site 3). At each of the 10 sites, NO_2 concentration was measured along a transect (1, 2, 3; panel d) with a greenbelt ("TREE") and an open transect without trees

("OPEN"). The distance of sampling points 1, 2 and 3 from the road at site 3 were 3 m, 13 m and 54 m, respectively (panel d).

2.2. Sampling sites and dates

We established ten sampling sites in which NO_2 collectors were placed along two adjacent parallel transects: one with a greenbelt and another without a greenbelt (open transect). The sampling sites were located in the Helsinki Metropolitan Area (two sites in the city of Helsinki, five in the city of Vantaa and three in the city of Espoo, Fig. 1b). The sampling sites were situated on the northern side of roads oriented in an east-west direction with moderate to large traffic volumes (Table 1). This ensured that air pollutant collectors resided downwind from traffic-derived air pollutants since the prevailing wind direction in the area is from south or south-west (see results). There were no major intersections or roads oriented in a south-north direction, or other close by major roads oriented in a west-east direction to the north of the measuring sites. Each transect contained three sampling points at varying distances from the road (see below).

The sampling sites were approximately at the same level (elevation) as the road surface. The open areas were meadows, grasslands or other treeless areas with short vegetation. The soil surface at these open areas was either completely pervious or partly impervious at walking and cycling paths. The greenbelts, either remnant forest patches or planted greenbelts, consisted of mature or semi-mature broadleaf and coniferous trees. There was always an open, treeless area behind the greenbelt. Although all sites resided in the urban environment, no buildings existed in close proximity to the transects (see Fig. 1d).

Table 1. Distances of the air samplers and greenbelt edges from the road edge and environmental variables measured at the 10 study sites in the Helsinki Metropolitan Area, arranged by ascending order of traffic volume of all vehicles (number of motor vehicles day^{-1}, annual average of daily traffic). Greenbelt width is the distance (m) between the front and back edge of the greenbelt. Values referring to trees were determined from a 10 x 10 m plot directly in front of the second distance sampler inside the greenbelt. Trees with a diameter at breast height (DBH) of < 2.54 cm (= 1 inch) are not included. Traffic volume of heavy vehicles includes only trucks and buses.

		Distance from the road edge (m)										
Site nr.	Site description: Road, Location	1. sampler	Green-belt front edge	2. sampler	Green-belt back edge	3. sampler	Green-belt width (m)	Total nr. of trees 100 m^{-2}	Nr. of trees with DBH > 16 cm 100 m^{-2}	% Broad-leaf trees	Traffic volume of all vehicles	Traffic volume of heavy vehicles
1	Turuntie, Jorvi	3	4	14	21	31	17	38	5	76	7,551	553
2	Kehä III, Hakunila	3	13	23	29	39	16	14	3	71	30,175	3,008
3	Kehä III, Kakolanmäki	3	3	13	44	54	41	24	13	100	44,335	3,901
4	Kehä III, Askisto	3	6	16	19	29	13	52	13	6	44,335	3,901
5	Lahdenväylä, Viikinmäki	3	3	13	17	27	14	47	9	100	46,975	2,963
6	Kehä III, Petikko	3	10	20	28	38	18	44	2	82	48,338	4,082
7	Turunväylä, Sepänkylä	3	13	23	46	56	33	67	4	97	54,096	2,578
8	Turunväylä, Nuijala	3	10	20	32	42	22	8	6	0	67,386	3,016
9	Kehä III, Tuupakka	3	12	22	23	33	11	82	5	96	68,314	6,544
10	Kehä III, Pukinmäki	3	12	22	38	48	26	44	3	100	69,466	3,528
mean		3	8.6	18.6	29.7	39.7	21.1	42	6.3	72.9	48,079	3,407

We mounted the NO_2 collectors under rain shields, attached to wooden poles or tree trunks (directly under the canopy). The rain shields were manufactured by IVL. We placed the collectors 1.5 - 2.0 m above ground representing the height at which humans are exposed to NO_2. Within each site at both transect types, we placed the collectors at the same distance from the edge of the road (a line marking the outer boundary of the road). The first measuring point at both transect types was 3 m from the road, always before the front edge of the greenbelt. At different sites, depending on the width of the greenbelt and its distance from the road, we placed the collectors at slightly different distances from the road. The second measuring point was inside the greenbelt and always 10 m from the front edge of the greenbelt. The distance of this 2nd measuring point from the road varied from 13 to 23 m (mean = 18.6 m). The third measuring point was in the open area behind the greenbelt and always 10 m from the back edge of the greenbelt. The distance of the 3rd measuring point from the road ranged between 27 and 56 m (mean = 39.7 m) (Table 1).

The size of the open area behind the greenbelt varied; at some sites a large open field continued hundreds of meters away from the road, while at other sites the open area was a narrow strip with a pedestrian/cycling route and after that again a continuous forest or another forest patch. The distance from the back edge of the greenbelt to the next forest edge ranged between 12 and 900 m (mean = 131.1 m). The front edge of the greenbelt was, on average, 8.6 m (3 – 13 m) and the back edge of the greenbelt, on average, 29.7 m (17 – 46 m) from the road edge. The width of the greenbelt (the distance between the greenbelt front and back edge, along the transect) ranged between 11 and 41 m (mean = 21.1 m). The length of the greenbelts (parallel to the road) ranged between 60 and 380 m (mean = 194.4 m). It was not always possible to place the transect in the middle of the greenbelt (length-wise) and we thus used the greenbelt width as a variable in data analysis, instead of greenbelt length or size. The area between the road and the front edge of the greenbelt was covered with short grass or meadow vegetation. In the open transects without trees, distance from the road to the next forest edge ranged between 45 and 500 m (mean = 110.5 m) and the estimated total open area ranged between 1,500 and 45,000 m^2 (mean = 9,970 m^2). Distance between the two transects (with or without a greenbelt) within each site ranged between 50 and 360 m (mean = 125.9 m). We carried out the sampling of NO_2 during summer, from 20 June to 1 August, 2016 (41 days), when plant leaves were fully developed, and during winter, from 24 November 2016 to 5 January, 2017 (42 days), when broadleaf trees were leafless, but coniferous trees had needles.

At each greenbelt, we determined the number, size and species of trees [only trees with a diameter at breast height, DBH > 2.54 cm (= 1 inch)] in a 10 x 10 m plot directly in front of the second sampling point (Table 1). The total number of trees recorded from 10 x 10 m plots was on average 42.0 ± 22.7, with large trees (DBH > 16 cm) comprising 23.1% (± 23.5) of all trees. The greenbelts were dominated by deciduous trees (72.9% ± 38.4), expect at two sites where the greenbelts were clearly dominated by coniferous trees. Forest tree species typical to southern Finland (*Salix* spp., *Populus* spp., *Pinus sylvestris*, *Sorbus aucuparia*, *Alnus* spp. and *Betula* spp.) were dominant with scattered *Ulmus glabra*, *Picea abies*, *Prunus padus* and *Acer platanoides*.

Traffic volume data [annual average volume of daily traffic (traffic volume of all vehicles and traffic volume of heavy vehicles separately), Table 1] were obtained from the Finnish Transport

Agency (2017). Mean annual NO_2 concentrations, measured at several sampling locations in the Helsinki Metropolitan Area in 2015, ranged between 4–49 µg m^{-3}, and do not usually exceed annual human health limits of 40 µg m^{-3}, except in highly trafficked locations as in our study (see also Kaski et al., 2016). Wind roses showing prevailing wind directions and speed during the measuring periods are shown in Fig. 2. The monthly average temperature in the Helsinki Metropolitan Area in July 2016 was 17.7 °C and in December 2016 -1.0 °C, representing typical temperatures in July and December in the area (Finnish Meteorological Institute, 2017).

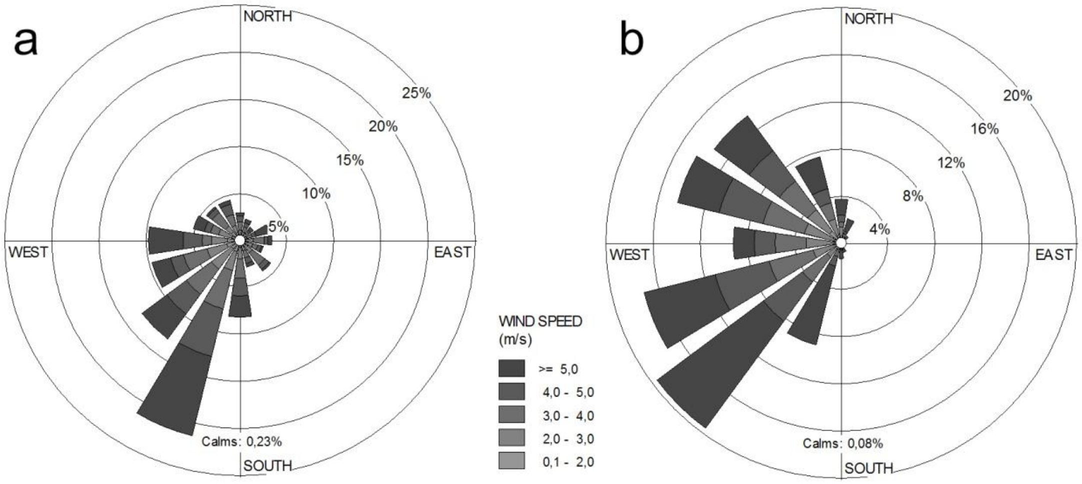


Fig. 2. Wind direction and speed during (a) 20 June – 1 August, 2016 and (b) 24 November, 2016 – 5 January, 2017 in Helsinki (Kumpula measuring station). Data were provided by the Finnish Meteorological Institute (FMI).

2.4. Data analysis

We tested changes in NO_2 concentrations using generalized linear mixed models, with NO_2 modelled following a normal distribution (after log transformation). The model included distance from the road edge as a factor (next to the road, ca. 20 m from the road, ca. 40 m from the road), transect type as a factor (with and without a greenbelt), season as a factor (summer, winter), their two- and three-way interactions, and traffic volume of all vehicles as a continuous variable. We included site as a random term in the model. We performed model selection by removing variables, one at a time, if their p-values were > 0.1. In practice, the three-way and some of the two-way interactions were removed using this procedure (see results).

Additionally, we performed Pearson correlations between greenbelt properties (greenbelt width, number of trees, number of large trees, proportion of broadleaf trees, traffic volume of all vehicles, traffic volume of heavy vehicles) and the level of NO_2 in front of these greenbelts to test the notion that greenbelts may act like barriers detaining polluted air in front of greenbelts. If the greenbelt does, in fact, act like such a barrier, we expect NO_2 concentrations to be higher in front of denser greenbelts.

Finally, we evaluated the effects of greenbelt properties on NO_2 levels inside the greenbelt and behind it. As such, we only used transects that include the greenbelt to perform two tests; i) the effects of greenbelt properties on NO_2 levels inside the greenbelt, and ii) the effects of greenbelt properties on NO_2 levels behind the greenbelt. We used two linear models (one each for NO_2 levels inside the greenbelt and NO_2 levels behind the greenbelt as response variable), including the following predictor variables; greenbelt width, number of trees, number of large trees, proportion of broadleaf trees, traffic volume of all vehicles, season (as a factor) and NO_2

concentration in front of the greenbelt as a covariate. Again, we performed model selection by removing insignificant terms (p-value > 0.1). All data analyses were performed using the R statistical software, version 3.3.2 (R Core Team, 2016).

3. Results

NO_2 concentrations were significantly higher in transects with a greenbelt compared to open transects (Table 2, Fig. 3), particularly so close to the roads. NO_2 levels in front of the greenbelts were significantly positively correlated with the number of trees in the greenbelt (summer: r = 0.65, p = 0.04, winter: r = 0.66, p = 0.04), and with traffic volume of heavy vehicles (trucks and buses) (summer and winter: r = 0.81, p = 0.004) (Fig. 4). Four of the predictor variables showed consistent effects on NO_2 concentrations inside and behind the greenbelt: concentrations (i) decreased with greenbelt width, (ii) increased with the number of large trees and traffic volume of all vehicles, and (iii) were higher during winter than summer (Table 3, Fig. 5). Furthermore, NO_2 concentrations inside the greenbelt increased with the proportion of broadleaf trees during both summer and winter. Also, NO_2 concentrations showed the following significant effects when both transect types were included; i) a decrease with distance from the road, and ii) higher levels during winter compared to summer (Table 2, Fig. 3).

Table 2. Generalized linear mixed effects model results (see Fig. 3), testing the effects of various predictor variables on NO_2 levels. Coefficients, standard errors (SE) and p-values are presented. Distance (3 m from the road), the open transect and the summer season are in the intercept.

Variable	Coefficient	SE	p
Intercept	2.906	0.204	

Distance (ca. 20 m from the road)	-0.374	0.049	< 0.001
Distance (ca. 40 m from the road)	-0.522	0.048	< 0.001
Transect (Greenbelt)	0.139	0.048	0.003
Season (Winter)	0.351	0.028	< 0.001
Traffic volume of all vehicles	6.652×10^{-6}	3.918×10^{-6}	0.090
Distance (ca. 20 m) x Transect (Greenbelt)	-0.027	0.068	0.686
Distance (ca. 40 m) x Transect (Greenbelt)	-0.129	0.068	0.058

Table 3. Linear model results (see Fig. 5), testing the effects of a number of greenbelt properties and road traffic volume of all vehicles on NO_2 concentrations inside the greenbelt and behind it. Coefficients, standard errors (SE) and p-values are presented.

Variable	Coefficient	SE	p
Sampling point inside the greenbelt*			
Intercept	11.530	3.572	0.006
Greenbelt width	-0.563	0.096	< 0.001
Number of large trees	1.119	0.227	< 0.001
Proportion of broadleaf trees	0.074	0.024	0.009
Traffic volume of all vehicles	0.0002	< 0.001	0.002
Season (Winter)	7.873	1.579	< 0.001
Sampling point behind the greenbelt**			
Intercept	15.040	2.789	< 0.001
Greenbelt width	-0.329	0.077	0.001
Number of large trees	0.369	0.190	0.074
Traffic volume of all vehicles	1.136×10^{-4}	4.005×10^{-5}	0.014
Season (Winter)	5.095	1.439	0.004

* $F_{5,14} = 15.27$, $p < 0.001$, adjusted $R^2 = 0.790$

** $F_{4,13} = 9.78$, $p < 0.001$, adjusted $R^2 = 0.674$

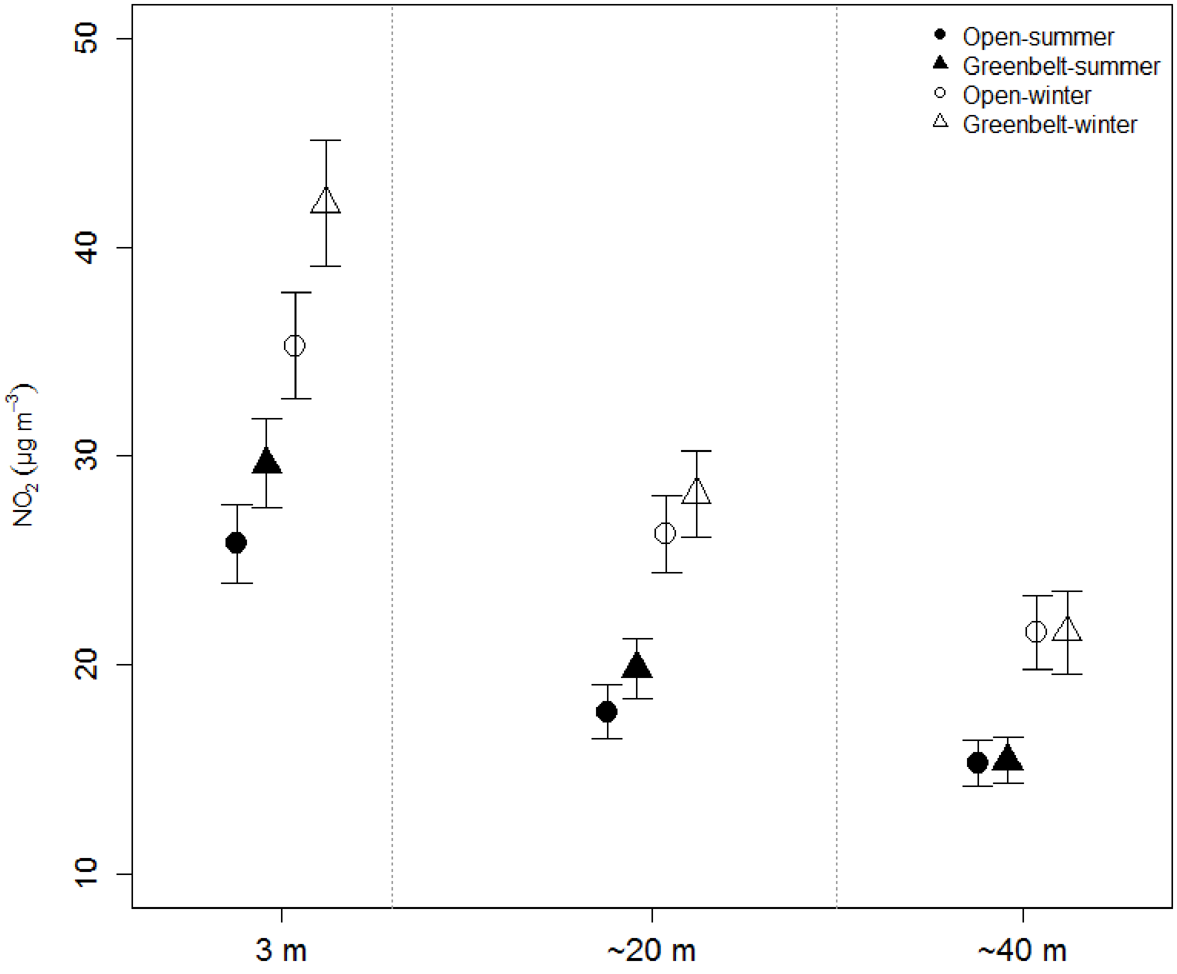


Figure 3. Predicted NO_2 concentrations (mean ± SE; n = 10 sites) in the open transect (circles) and the transect with a greenbelt (triangles) at different distances from the road edge, classified as 3 m, ca. 20 m and ca. 40 m, in summer (black) and winter (open symbols). The dotted lines represent the greenbelt's front and back edge.

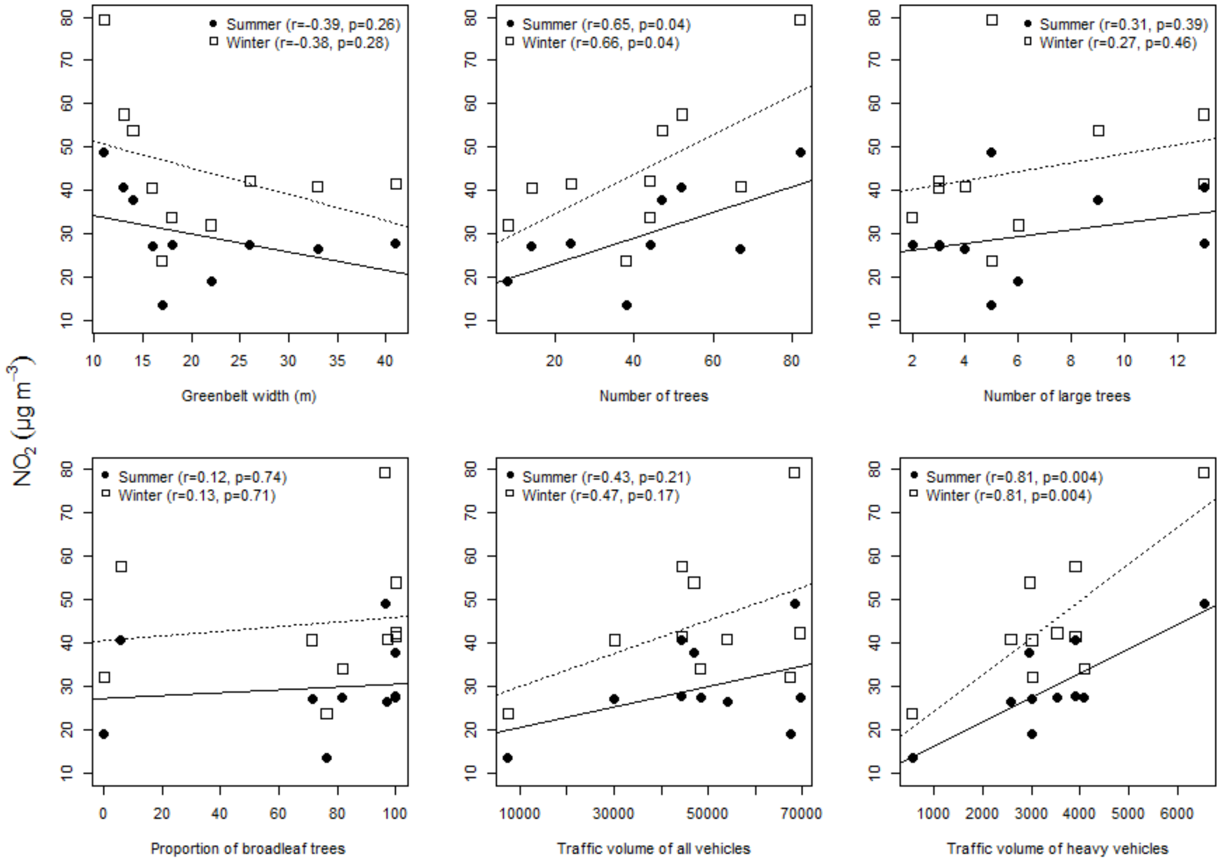
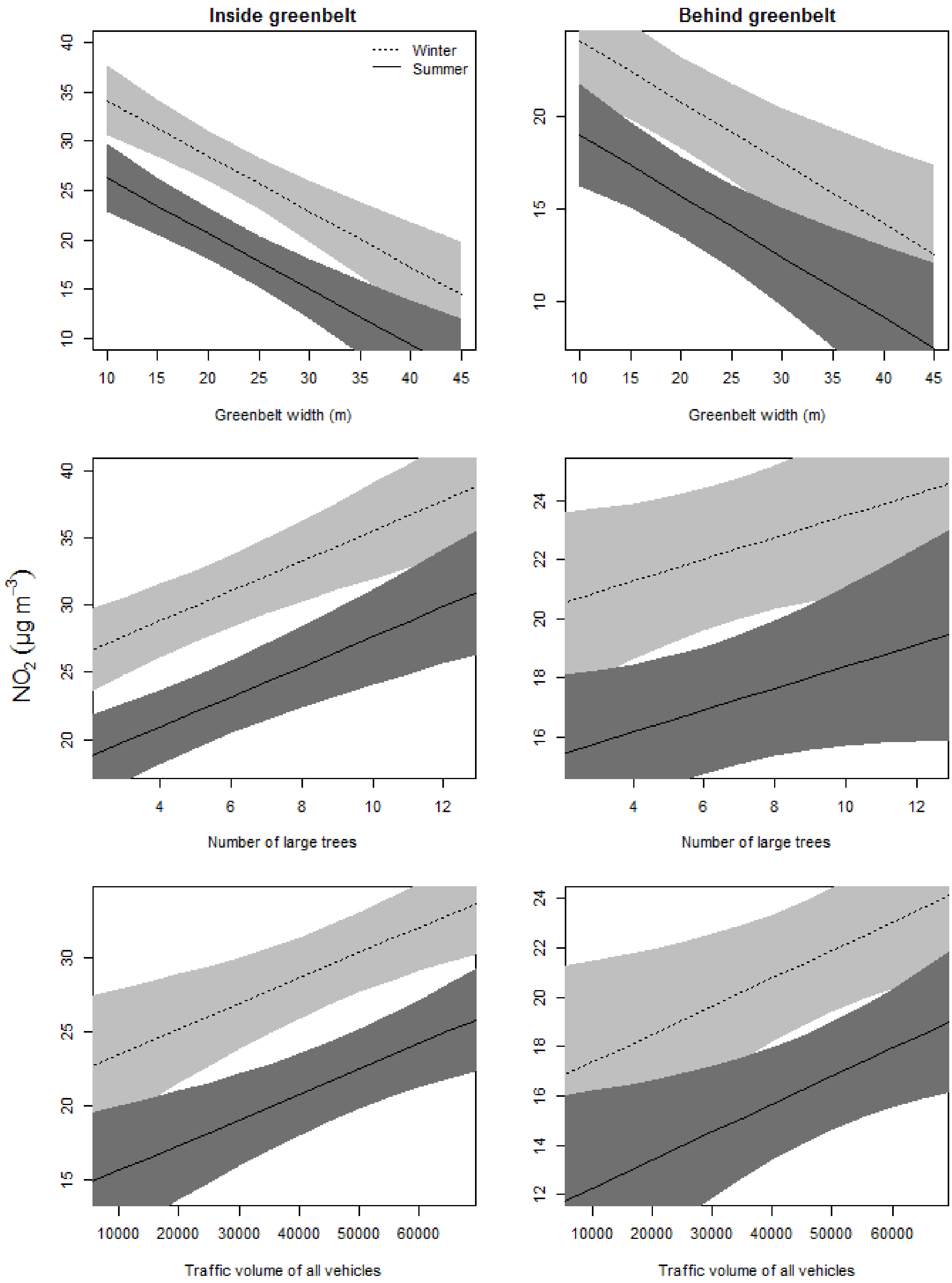


Figure 4. Correlations between NO$_2$ concentrations at the roadside (i.e., in front of the greenbelt) and various greenbelt properties, as well as traffic volume of all vehicles and traffic volume of heavy vehicles (number of motor vehicles day^{-1}, annual average of daily traffic) in summer and winter.


Inside greenbelt
Behind greenbelt
Winter
Summer
NO$_2$ (µg m^{-3})
Greenbelt width (m)
Greenbelt width (m)
Number of large trees
Number of large trees
Traffic volume of all vehicles
Traffic volume of all vehicles
10
15
20
25
30
35
40
45
4
6
8
10
12
10000
20000
30000
40000
50000
60000

134

Figure 5. Linear model results, indicating the relation between NO_2 concentrations inside the greenbelt (left panels) and behind the greenbelt (right panels), with greenbelt width, number of large trees and traffic volume of all vehicles (number of motor vehicles day^{-1}, annual average of daily traffic) in summer and winter. Grey areas represent standard errors (see Table 3 for details). Note different scales between left and right panels.

4. Discussion

Our study, performed during hemi-boreal summer- and wintertime, suggests that greenbelts composed mostly of broadleaf trees do affect local air quality, here NO_2 concentrations, but mostly negatively. This effect was, irrespective of season, largely the same in front of and inside greenbelts, while negligible behind them, suggesting that such vegetation structures can efficiently alter pollution and microclimatic conditions, such as air flow, in near-road environments. Judged by the decreased NO_2 levels with distance from the road when both transect types were included, and the positive correlation between NO_2 levels and traffic volume in transects with greenbelts (see also Clements et al., 2009), we are confident that the main source of NO_2 at our study sites was road traffic. Next we tackle air quality changes in front of, and inside and behind greenbelts.

4.1. NO_2 concentrations in front of greenbelts

The higher NO_2 levels in front of greenbelts relative to those observed at roadsides without greenbelts supports our hypothesis, according to which reduced dilution and mixing of traffic-derived polluted air in front of greenbelts results in increased pollutant concentrations. This effect is possibly due to the formation of a recirculation zone of air between the road and the greenbelt front edge, as suggested by Baldauf et al. (2008) and Tong et al. (2016) regarding particulate matter, the effect of which is likely reinforced by dense vegetation at the greenbelt front edge. Indeed, we found a positive correlation between NO_2 levels in front of greenbelts and the number of trees inside greenbelts, corresponding to denser vegetation structure. This, in turn, acts like a barrier that reduces dilution and detains polluted air in front of the greenbelt (see Al-Dabbous & Kumar, 2014; Ning et al., 2010). The recirculation of particulates and gaseous pollutants by physical obstacles has been well documented in urban street canyons where building walls and other solid structures reduce natural ventilation in highly polluted environments (e.g. Vardoulakis et al., 2003; Xie et al., 2003). Although previous studies from other parts of the world have suggested that roadside greenbelts can filter particulate matter and thus improve local air quality behind greenbelts - or in some cases increase particulate matter concentrations due to certain characteristics (height, thickness, porosity, length) of the vegetative barriers (Al-Dabbous & Kumar, 2014; Baldauf, 2017; Hagler et al., 2012; Islam et al., 2012; Tong et al., 2016), we are not aware of previous studies in which belt-like vegetative structures have been studied in terms of the gaseous pollutant NO_2. Our results suggest that one should not take for granted the notion that greenbelts necessarily provide overall air quality benefits in near-road environments. For instance, placing routes for pedestrians and cyclists between heavily trafficked roads and dense greenbelts can result in elevated NO_2 exposure compared to routes with better ventilation and dilution of air pollutants.

4.2. NO_2 concentrations inside and behind greenbelts

Although we expected NO_2 levels inside greenbelts to be the same as or slightly lower than at the same distance from the road without greenbelts (see Setälä et al., 2013; Yli-Pelkonen et al., 2017), we, unexpectedly, found significantly higher NO_2 concentrations inside greenbelts. This is in agreement with Harris & Manning (2010), who showed that NO_2 levels can be higher within urban tree canopies than outside them. They suggested that this, at least partly, results from NO_x/O_3 chemistry related to gas interactions between soil and the air, as described by Fowler (2002), and that NO_2 concentrations under tree canopies would be high when ambient NO_2 levels are high. However, because NO_2 levels were also higher inside the greenbelts during winter with frozen soil and snow cover, NO_x emissions from the soil unlikely explain our findings. The forest canopy can also reduce NO_2 concentrations: Grundström & Pleijel (2014), in their near-road study in southern Sweden, reported slightly lower NO_2 concentrations within the forest canopy (7%) compared to a nearby open sampling point. Likewise, Fantozzi et al. (2015) found lower NO_2 concentrations within a *Quercus ilex* L. (Mediterranean evergreen) forest transect situating 1-10 m from the road than in an adjacent open-field transect. Thus, the impact of vegetation on gaseous pollutant concentrations may depend on vegetation type and local climatic conditions. In essence, tree species at our study sites growing in cool climate may be less efficient in absorbing and processing NO_2 compared to trees in warmer climates. Consequently, the amount of NO_2 absorbed by vegetation through stomatal intake in our study - even during Nordic summers - was negligible in relation to ambient pollutant concentrations inside the greenbelts.

We suggest that the higher NO_2 levels inside greenbelts are explainable by divergent wind patterns between greenbelts and open, treeless areas. Since the tree canopy can reduce flow, dilution and mixing of polluted air (Belcher et al., 2012; Gromke & Ruck, 2009; Renaud et al., 2011; Wuyts et al., 2008), these effects can increase pollutant levels inside the canopy, as reported by, e.g. Harris & Manning (2010), Setälä et al. (2013), Viippola et al. (2016) and Vos et al. (2013). In the absence of greenbelts or other tree cover, polluted air mass dilutes more rapidly by higher wind velocity, which brings about lower pollutant concentrations in open areas. The role of greenbelts in decreasing air flow is further emphasized by our result showing that concentrations of NO_2 inside greenbelts increased with number of large trees. Since larger trees are also taller and have larger canopy coverage than smaller trees, this facilitates polluted air to become more readily "trapped" underneath the canopy (e.g. Belcher et al., 2012). In addition, it is possible that the elevated NO_2 levels in front of greenbelts in our study were, at least partly, responsible for the higher pollutant concentrations inside greenbelts, given that traffic-derived polluted air mass eventually ends up downwind into the greenbelts. Overall, although NO_2 levels inside the greenbelts were slightly higher compared to open areas without greenbelts, our results suggest that wider greenbelts absorb NO_2 more efficiently than narrow ones.

In contrast to our hypothesis, concentrations of NO_2 behind greenbelts did not differ from those without greenbelts, suggesting that greenbelts do not block pollution transport efficiently enough to reduce NO_2 concentrations behind the greenbelt. This unexpected result may be explainable by large trees in the greenbelt creating a downwind recirculation zone of air pollutants behind the greenbelt and consequently elevating NO_2 concentrations behind the greenbelt so that the potential reduction of NO_2 levels by the greenbelt cannot be detected (Detto et al., 2008; Steffens et al., 2012; Tong et al., 2015). The relation between increasing greenbelt width and lower NO_2 levels behind the greenbelt is not surprising since greenbelt width correlated significantly positively with NO_2 sampling distance (behind the greenbelt) from the road ($r = 0.92$, $p < 0.001$). Our results suggest that, regarding NO_2, building greenbelts between busy roads and, e.g. recreation routes or places for sensitive groups (children, the elderly), with the aim at better air quality behind the greenbelt, should be addressed with utmost care.

4.3. Impacts of season and local wind conditions on NO_2 concentrations

To explore the influence of foliage in pollution removal we conducted air sampling when total leaf area and gas exchange between leaves and ambient air is either high (summer) or low (winter) (Rautiainen et al., 2012). Our results corroborate earlier findings that NO_2 levels within road-side forests in early (Yli-Pelkonen et al., 2017) and late (Setälä et al., 2013) Nordic summers are not reduced by vegetation. Neither did the greenbelts lower NO_2 levels during winter, which is in accordance with results reported by Setälä et al. (2013), although in the current study NO_2 levels were elevated within the greenbelts also during the leafless period. This unexpected observation implies that the role of greenbelt vegetation in affecting the levels of gaseous pollutants, such as NO_2, is not strictly related to biological processes (such as gas absorption by the foliage) but rather to factors related to the control of air flow. For example, vegetation can reduce wind speed not only during the leaf period (Setälä et al., 2013) but also during the leafless period, as has been shown by Renaud et al. (2011) in deciduous forests in Switzerland. Although such reduced ventilation can increase pollutant levels within green infrastructures during summer (Viippola et al., 2016), no one has, to our knowledge, documented this to take place during leafless periods in winter. The increase in NO_2 levels inside the greenbelts with (i) the number of large trees and (ii) the proportion of broadleaf trees also in winter, further suggests that large canopy structures, also without leaves, can reduce air movement under them leading to higher NO_2 levels.

Our sampling sites resided, for most of the campaign periods, downwind or at least in a neutral position relative to the major pollution source, roads (Fig. 2). Besides, our rather long sampling periods, ca. 6 weeks, should reduce the effects of short-term wind directional changes and thus improve reliability of our results. The observed higher NO_2 concentrations in winter than summer (Fig. 3) are typical to northern latitudes due to reduced mixing and dilution of polluted air during cold and calm weather (Kaski et al., 2016). NO_2 concentrations at our study sites generally equaled the latest available mean annual and monthly concentrations in the Helsinki Metropolitan Area (Kaski et al., 2016). However, at the roadsides of 7 sites during winter, NO_2 concentrations exceeded the annual limit for human health by up to 2 times (mean = 28%) (see Fig. 4) (Air quality in Finland, 2017; Kaski et al., 2016). At all 7 sites, wintertime exceedance occurred in front of the greenbelt and at 3 sites also at the roadside without the greenbelt. During summer, the annual limit for human health was exceeded at only 2 sites (mean exceedance 12%) and only in front of the greenbelt. As the annual limit of NO_2 for human health was not exceeded inside or behind the greenbelts at all, the zone very close to the road - with or without a greenbelt - and especially the area between the road and the greenbelt are the most crucial areas regarding human health impacts.

5. Conclusions

As regards to pollution mitigation, greenbelts did not always function as expected. The result that NO_2 levels were elevated in front of greenbelts was in line with our hypothesis and likely results from the formation of a recirculation zone of air flow that reduces dilution and partly detains the polluted air in front of the greenbelt edge, increasingly so when a greenbelt has dense tree cover (see also Tong et al., 2016). This suggests that, for instance, regular and long-term use of a walking or cycling route parallel to a busy road in front of a dense greenbelt with extensive canopy causes higher exposure to NO_2 than when using a similar route without a greenbelt.

The unexpected elevated NO_2 concentrations inside greenbelts compared to transects without them indicate that reduced wind flow under the canopy, with or without leaves, was responsible for the increased NO_2 levels inside greenbelts. The greenbelts in our study were dysfunctional in terms of improving air quality behind greenbelts, regarding NO_2. Thus, if pedestrian or cycling routes, or other sensitive entities, such as schools, day-care centers or children's playgrounds are situated right behind a greenbelt, the benefits provided by greenbelts are likely associated with profits or ecosystem services other than the removal of NO_2.

Our results suggest that actions targeted to local air pollution mitigation should take account of local differences in vegetation, climate, micro-climate, and traffic conditions. Furthermore, it seems likely that adequate distance from the pollutant source, i.e. busy road, is - with or without greenbelts - a safe measure to reduce human exposure to NO_2 and other traffic-derived pollutants.

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References

Air quality in Finland (2017). Retrieved January 18, 2017 from - http://www.ilmanlaatu.fi

Al-Dabbous, A.N., Kumar, P. (2014). The influence of roadside vegetation barriers on airborne nanoparticles and pedestrians exposure under varying wind conditions. Atmospheric Environment 90, 113–124.

Anttila, P., Tuovinen, J-P., Niemi, J.V. (2011). Primary NO_2 emissions and their role in the development of NO_2 concentrations in a traffic environment. Atmospheric Environment 45, 986–992.

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.

Baldauf, R. (2017) Roadside vegetation design characteristics that can improve local, near-road air quality. Transportation Research Part D 52, 354–361.

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.

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.

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

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.

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.

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.

Chen, L., Liu, C., Zou, R., Yang, M., Zhang, Z. (2016). Experimental examination of effectiveness of vegetation as bio-filter of particulate matters in the urban environment. Environmental Pollution 208, 198–208.

Clements, A.L., Jia, Y., Denbleyker, A., McDonald-Buller, E., Fraser, M.P., Allen, D.T., Collins, D.R., Michel, E., Pudota, J., Sullivan, D., Zhu, Y. (2009). Air pollutant concentrations near three

Texas roadways, Part II: Chemical characterization and transformation of pollutants. Atmospheric Environment 43, 4523–4534.

Detto, M., Katul, G.G., Siqueira, M., Juang, J.-Y., Stoy, P. (2008). The structure of turbulence near a tall forest edge: the backward-facing step flow analogy revisited. Ecological Application 18, 1420–1435.

Duncan, B.N., Lamsal, L.N., Thompson, A.M., Yoshida, Y., Lu, Z., Streets, D.G., Hurwitz, M.M., Pickering, K.E. (2016). A space-based, high-resolution view of notable changes in urban NO_x pollution around the world (2005-2014). Journal of Geophysical Research 121, 976–996.

EEA (2016). Air quality in Europe – 2016 report. European Environment Agency EEA Report No 28/2016. Retrieved December 2, 2016 from - http://www.eea.europa.eu/publications/air-quality-in-europe-2016

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.

Ferm, M., Rodhe, H. (1997). Measurements of air concentrations of SO_2, NO_2 and NH_3 at rural and remote sites in Asia. Journal of Atmospheric Chemistry 27, 17–29.

Finnish Meteorological Institute (2017). Open meteorological data. Retrieved 15 January, 2017 from - http://ilmatieteenlaitos.fi/avoin-data

Finnish Transport Agency (2017). Traffic volumes. Retrieved 15 January, 2017 from - http://www.liikennevirasto.fi/web/en/maps-charts/traffic-volumes

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

Gallagher, J., Baldauf, R., Fuller, C.H., Kumar, P., Gill, L.W., McNabola, A. (2015). Passive methods for improving air quality in the built environment: A review of porous and solid barriers. Atmospheric Environment 120, 61–70.

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.

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.

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.

Hagler, G.S.W., Tang, W., Freeman, M.J., Heist, D.K., Perry, S.G., Vette, A.F. (2011). Model evaluation of roadside barrier impact on near-road air pollution. Atmospheric Environment 45, 2522–2530.

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

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

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.

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.

Kampa, M., Castanas, E. (2008). Human health effects of air pollution. Environmental Pollution 151, 362–367.

Kaski, N., Aarnio, P., Loukkola, K., Portin, H. (2016). Ilmanlaatu pääkaupunkiseudulla vuonna 2015 (Air Quality in the Helsinki Metropolitan Area in 2015). HSY (Helsinki Region Environmental Services Authority) publications 6/2016. [in Finnish with an abstract in English]

Klingberg, J., Broberg, M., Strandberg, B., Thorsson, P., Pleijel, H. (2017) Influence of urban vegetation on air pollution and noise exposure – A case study in Gothenburg, Sweden. Science of the Total Environment 599-600, 1728–1739.

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.

Krämer, U., Koch, T., Ranft, U., Ring, J., Behrendt, H. (2000). Traffic-related air pollution is associated with atopy in children living in urban areas. Epidemiology 11, 64–70.

Loukkola, K., Koskentalo, T., Humaloja, T. (2004) Passiivikeräinmenetelmän uudistaminen syksyllä 2003. YTV Ympäristötoimisto. [in Finnish] Retrieved 15 May, 2017 from - https://www.hsy.fi/sites/Esitteet/EsitteetKatalogi/Raportit/2_2004_passiivikerain_uudistaminen2003.pdf

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.

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.

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.

Ning, Z., Hudda, N., Daher, N., Kam, W., Herner, J., Kozawa, K., Mara, S., Sioutas, C. (2010). Impact of roadside noise barriers on particle size distributions and pollutants concentration near freeways. Atmospheric Environment 44, 3118–3127.

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

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.

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.

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.

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.

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.

R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved 1 March, 2017 from - https://www.R-project.org/

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.

Renaud, V., Innes, J.L., Dobbertin, M., Rebetez, M. (2011). Comparison between open-site and below-canopy climatic conditions in Switzerland for different types of forests over 10 years (1998-2007). Theoretical and Applied Climatology 105, 119–127.

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.

Selmi, W., Weber, C., Rivière, E., Blond, N., Mehdi, L., Nowak, D. (2016). Air pollution removal by trees in public green spaces in Strasbourg city, France. Urban Forestry & Urban Greening 17, 192–201.

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.

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.

Sulistyantara, B., Nasrullah, N., Fatimah, I.S., Pratiwi, P.I. (2016). Study on the effectivity of several tree canopy types on the roadside green belt in influencing the distribution vertically and horizontally of CO gas emitted from transportation activities to vicinity of the road. Earth and Environmental Science 31, 012031.

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.

Tong, Z., Baldauf, R.W., Isakov, V., Deshmunk, P., Zhang, K.M. (2016). Roadside vegetation barrier design to mitigate near-road air pollution impacts. Science of the Total Environment 541, 920–927.

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.

Vardoulakis, S., Fisher, B.E.A., Pericleous, K., Gonzalez-Flesca, N. (2003) Modelling air quality in street canyons: a review. Atmospheric Environment 37, 155–182.

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.

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.

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.

Xie, S., Zhang, Y., Qi, L., Tang, X. (2003). Spatial distribution of traffic-related pollutant concentrations in street canyons. Atmospheric Environment 37, 3213–3224.

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.

Yli-Pelkonen, V., Setälä, H., Viippola. V. (2017). Urban forests near roads do not reduce gaseous air pollutant concentrations but have an impact on particles levels. Landscape and Urban Planning 158, 39–47.