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Short communication

Limited effect of urban tree vegetation on NO_2 and O_3 concentrations near a traffic route

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ABSTRACT

Concentrations of NO_2 and O_3 were measured inside and outside a dense broad-leaved forest canopy adjacent to a busy traffic route in the City of Gothenburg, Sweden, with duplicate passive diffusion samplers during six one-week periods starting well before leaf senescence and ending when leaves were largely senescent. Concentrations of NO_2 were lower inside the forest canopy during all periods (representing a significant effect, $p = 0.016$), on average by 7% or 2.7 $\mu g\ m^{-3}$. O_3 showed a more variable response with an average non-significant effect of 2% lower in the forest stand. There was no systematic trend of the difference in concentrations inside and outside the forest stand of the pollutants with the progression of autumn leaf senescence. Our study indicates that the effect of urban vegetation on air pollution concentrations is small, although it seems to exist for NO_2 in a traffic polluted environment.

1. Introduction

Vegetation has a multitude of functions to improve the urban environment, including biodiversity, improved microclimate, reduced greenhouse gas emissions, storm-water runoff mitigation and noise reduction (Pataki et al., 2011; Lindberg and Grimmon, 2011; Heyman et al., 2011). One further service that urban vegetation can provide is improved air quality. This will reduce air pollution effects on human health and vegetation (Nowak et al., 2006). Vegetation can alter the occurrence of air pollutants in the urban landscape both by deposition and by affecting the physical transport of polluted air masses, e.g. by reducing ventilation of street canyons (e.g. Salmond et al., 2013) or enhancing ventilation by increasing surface roughness and thus turbulence.

The extent to which urban vegetation can promote improved air quality has mostly been explored using models. For example, the modelling study by Nowak et al. (2006) concluded that there is a large mass flux of air pollutants to urban vegetation from a large geographical perspective (US). These fluxes did not result in very substantial effects on local air pollution concentrations, although even small concentration reductions affecting large populations represent significant gains in human health. It has, however, been suggested that the role of urban vegetation in reducing local air pollution has been exaggerated (Pataki et al., 2011).

Nitrogen dioxide (NO_2) is a traffic related air pollutant having strongly elevated levels in areas with abundant traffic (Pleijel et al., 2004) for which air quality standards exist. It affects human health (Samoli et al., 2006) and vegetation such as epiphytic lichens (Hultengren et al., 2004). Ozone (O_3), on the other hand, is a secondary, regionally occurring pollutant, which is also known to affect health (Vagaggini et al., 2002) in addition to effects on vegetation (Mills et al., 2011).

Fewer direct empirical investigations of the effect of urban vegetation on air quality have been undertaken compared to modelling studies (Setälä et al., 2013). These authors recently published a detailed study of the effects of urban vegetation on air pollution in two cities in Finland. Their study indicated the effect of urban vegetation on local air pollution to be small. In the case of $[NO_2]$ there was a small non-significant negative effect by vegetation, which did not differ between seasons. Volatile organic compounds effects were small and inconclusive, while particle reductions by vegetation were somewhat larger (Setälä et al., 2013). Harris and Manning (2010) investigated $[NO_2]$ and $[O_3]$ inside and outside the canopies of individual *Acer rubrum* trees with varying distances from traffic. They found $[O_3]$ to be lower but $[NO_2]$ to be higher inside the tree canopies. These authors explained the observations with NO_x/O_3 chemistry in combination with emission/deposition conditions.

To improve the empirical understanding of the effects of urban vegetation on local air pollution we compared $[NO_2]$ and $[O_3]$ near a major traffic route outside and inside a dense deciduous forest stand using passive diffusion samplers. The hypothesis was that the

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concentrations of the pollutants would be lower inside the forest canopy.

2. Materials and methods

[NO_2] and [O_3] were monitored using duplicate (two parallel samplers inside and two outside the forest stand, $n = 2$) passive diffusion samplers of the IVL type (http://www.diffusivesampling.ivl.se/). Samplers were placed under opaque rain shelters. The measurements were conducted during six one-week periods starting 10 September and ending 21 October 2010. The measurement site was situated at a busy traffic route (113 000 vehicles per day in 2010) 2 km east of the city centre of Gothenburg, south-west Sweden (57°42.97′N, 11°59.63′E). The traffic route forms part of a larger system of roads and the green space where the measurements were undertaken is surrounded by roads with intensive traffic. An aerial picture of the area where the measurements were conducted is shown in Fig. 1.

Measurements were undertaken outside and inside a dense canopy of 8–10 m tall mixed broadleaved trees. The edge of the forest stand had a high density of leaves all the way down to the ground (see Fig. 1) and should represent a strong case in terms of dense vegetation in contrast to the nearby measurement point outside the canopy, which was exposed directly to the traffic exhausts. The measurement points were 8 m and 12 m from the closest lane of the traffic route. Measurement height was 3.5 m. In addition, temperature was measured at the two sites (1.5 m height) using TinyTag (TGP 4500) loggers. At the start of the measurements the vegetation was lush green, but turned subsequently more senescent during the measurement period. In order to represent the degree of senescence and light exclusion of the canopy, solar radiation was measured inside and outside the canopy each time the passive diffusion samplers were changed using a portable LI-COR Integrated Quantum/Radiometer/Photometer (LI-188B). Measurements were repeated ten times in each environment on each occasion. Wind speed and direction were measured at a rooftop (30 m above street level) monitoring station 2 km W of the investigation site (Gill ultrasonic anemometer).

3. Results and discussion

In Table 1 temperatures for the six periods are presented. At the start of the investigation temperatures at the two sites were very similar. At the end of the period the tree stand was slightly warmer than the open space, which is likely explained by being sheltered by the canopy and thus less affected by heat radiation loss, which becomes more important as the autumn progresses and nights become longer and cooler. When the measurements started, light exclusion of the forest stand was estimated at around 95%, and was reduced to less than 75% at the end. Winds directions were rather variable during the six measurement periods, but for the extent of the full period all wind directions were on average relatively equally represented, southerly winds being most common and westerlies least abundant.

Table 2 shows [NO_2] for the six one-week periods. The duplicate measurements agreed very well. The average coefficient of variation for the pairs of NO_2 observations was 1.5%, pointing towards high precision. [NO_2] was higher outside the canopy during all six periods, although to a varying degree; the ratio between [NO_2] inside and outside the canopy was in the range 0.90–0.98. The average ratio was 0.93, i.e. a concentration reduction by ~7% or 2.7 $\mu g\ m^{-3}$. This is similar in magnitude to the average effects of urban trees in 11 US cities modelled by Nowak et al. (2006) which were in the range of 1.1–2.8 $\mu g\ m^{-3}$, although the values are not fully comparable. Applying a binomial sign test (Bailey, 1995) to our data suggest that the difference in concentration was statistically significant ($p = 0.016$). Thus, our data indicate that there is an effect of urban forest vegetation on local [NO_2], but that it is rather limited. There were relatively high ambient [NO_2] and a strong contrast in conditions between the dense canopy and the adjacent open space. In such a situation, effects of vegetation on pollution concentration should have a large possibility to become manifest and be detected. The result is in line with the conclusions of Pataki et al. (2011) and Setälä et al. (2013) that most studies show that urban vegetation have small effects in terms of air pollution concentrations. The effect on [NO_2] did not vary systematically with time, i.e. with the progress of canopy senescence.

In the case of O_3 (Table 3) the average reduction in concentration by the canopy was 2% and not significant. In two periods [O_3] was indicated to be slightly higher inside the canopy. The average coefficient of variation for pairs of replicate O_3 observations was 2.5%, higher than for NO_2, but still indicating good precision. Unlike NO_2, O_3 is not a local pollutant but a regional. Near traffic routes with high [NO], O_3 can be chemically consumed (Fowler et al., 1998). On

Fig. 1. Aerial view of the measurement site in the City of Gothenburg, south-west Sweden as well as a photo of the measurement site showing the measurement point outside the canopy and the forest edge inside which the measurement point inside the canopy was situated. The two measurement points were 4 m apart.

Table 1
Temperatures at the measurement site inside and outside the tree canopy for the six one-week measurement periods as well as the fraction of solar radiation inside vs. outside the tree stand to represent the degree of senescence. Solar radiation was expressed as Photosynthetically active photon flux density (μmole m^{-2} s^{-1}). In addition, average wind speed and the frequency distribution of wind directions in the four main 90° wind sectors during the six measurement periods are presented.

Period	Temperature °C	Temperature °C	Solar radiation	Wind speed m s^{-1}	Wind direction			
	Inside canopy	Outside canopy	Fraction inside vs. outside canopy		N, %	E, %	S, %	W, %
10 Sep–16 Sep	14.5	14.7	0.05	4.3	2	4	57	37
16 Sep–23 Sep	12.3	12.3	0.04	4.7	1	11	44	44
23 Sep–30 Sep	10.8	10.8	0.05	4.2	72	11	16	1
30 Sep–7 Oct	11.6	11.6	0.11	4.9	2	80	17	1
7 Oct–14 Oct	8.4	8.2	0.28	2.3	45	36	9	10
14 Oct–21 Oct	5.0	4.6	0.26	3.3	47	12	35	6
Average	10.4	10.4		4.0	28	26	30	16

the other hand, vertical mixing of the air, which is promoted by rough surfaces such as tree stands, enhances [O_3] near the ground, since O_3 lost by deposition is more efficiently replenished by O_3 from aloft.

The correlation between the ratio inside and outside the forest canopy of [NO_2] and [O_3], respectively, and the fraction of time with different wind directions during the six measurement periods was tested (Table 4). For NO_2, no statistically significant correlations were obtained, but it was indicated that the north-south wind directions were of larger importance than west-east wind directions, southerly winds resulting in the largest reduction in [NO_2] in the forest canopy. For O_3 a similar pattern was found, but in this case the correlation with southerly and anticorrelation with northerly wind directions of the ratio between the concentration inside and outside the forest canopy were statistically significant ($p < 0.05$). There is no obvious explanation for the NO_2 pattern, since the most nearby traffic route was roughly situated to the west of the measurement site (Fig. 1). However, the wind direction needs consideration when assessing the effects of forest stands and other vegetation on urban air pollution levels. In the case of O_3, the explanation could be that with northerly wind the air is moving over the rougher forest surfaces (Fig. 1), enhancing vertical transport as stated above. In fact, in the measurement periods with a large fraction of northerly wind, the concentration of O_3 was indicated to be equal to or slightly higher inside the canopy than outside (Tables 1 and 3).

In contrast to our study and Setälä et al. (2013), Harris and Manning (2010) found higher [NO_2] inside canopies of individual *Acer rubrum* tree canopies compared to outside. This effect had varying magnitude, but was consistent over two years. Harris and Manning (2010) discuss, following Fowler (2002), that oxidation of O_3 by NO emitted by the plant–soil system might result in formation of NO_2 inside the canopy, this process being dominant over deposition only at low to moderate [NO_2]. At high [NO_2], according to this line of argument, the canopy would act as a net sink for NO_2. It can be noted that [NO_2] was higher in our study compared to Harris and Manning (2010), which might explain the discrepancy between the two studies. We believe that in our case the NO emissions of the rather small forest stand would be limited compared to the local pollution generated by intensive traffic.

Regional O_3 will tend to react with exhaust NO leading to formation of NO_2 (Fowler et al., 1998). If this reaction is more prominent outside the canopy it would lead to an underestimation of the canopy effect on [NO_2] caused by deposition and an overestimation of the canopy effect on [O_3] deposition. Since [O_3] was not very different between the open space and the canopy, this is not likely to have been very important for our conclusion on the effect of the forest canopy on [NO_2], but it may have led to some underestimation of this effect.

To conclude, although our study only represents one measurement point, it shows that even in a situation with strongly contrasting conditions within and outside a dense tree canopy, and with relatively high concentrations [NO_2], was only reduced by the vegetation cover to a limited, even though significant, extent. Thus, it is not justified to expect large effects of urban vegetation on local gaseous pollutants by deposition but small air quality changes can impact human health. If influencing large populations, they will translate into considerable health benefits (Nowak et al., 2006). For

Table 2
Concentrations (μg m^{-3}) of NO_2 inside and outside a dense tree canopy near a traffic route during six one-week periods and the ratio between the concentration inside and outside the tree stand. Concentrations are averages of two duplicate samplers. SD represents the standard deviation of the duplicate measurements.

Period	Inside tree canopy		Outside canopy		Ratio
	Average	SD	Average	SD	
10 Sep–16 Sep	42.2	0.96	47.1	0.52	0.90
16 Sep–23 Sep	42.6	0.05	45.5	1.94	0.94
23 Sep–30 Sep	21.1	0.01	21.6	0.24	0.98
30 Sep–7 Oct	20.1	0.18	21.6	0.92	0.93
7 Oct–14 Oct	28.0	0.11	30.2	0.04	0.93
14 Oct–21 Oct	37.6	0.65	41.3	0.37	0.91
Average	31.9	0.33	34.6	0.67	0.93

Table 3
Concentrations (μg m^{-3}) of O_3 inside and outside a dense tree canopy near a traffic route during six one-week periods and the ratio between the concentration inside and outside the tree stand. Concentrations are averages of two duplicate samplers. SD represents the standard deviation of the duplicates.

Period	Inside canopy		Outside canopy		Ratio
	Average	SD	Average	SD	
10 Sep–16 Sep	23.5	1.38	25.8	1.52	0.91
16 Sep–23 Sep	25.7	0.56	27.8	0.08	0.93
23 Sep–30 Sep	27.6	0.20	26.9	0.33	1.02
30 Sep–7 Oct	33.2	0.12	34.2	0.53	0.97
7 Oct–14 Oct	12.9	0.73	12.3	0.04	1.05
14 Oct–21 Oct	19.8	0.61	19.8	1.06	1.00
Average	23.8	0.60	24.5	0.59	0.98

Table 4
Correlation coefficient (R) and statistical significance (p) of the relationships between the ratio inside-to-outside the forest canopy of [NO_2] or [O_3] and the time fraction of wind direction. $N = 6$.

		N	E	S	W
NO_2	R	−0.56	−0.06	0.60	0.40
	p	0.25	0.91	0.21	0.44
O_3	R	−0.83	−0.21	0.87	0.79
	p	0.035	0.69	0.021	0.06

the regional pollutant O_3 no substantial effect was detected, which may be the net result of counteracting processes (deposition vs. down-mixing from air layers above the trees). Finally, to improve our understanding of the effect of urban vegetation on local air pollution further well-designed measurements are required. As pointed out by Setälä et al. (2013) current opinions on these matters are presently dominated too much by modelling.

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