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Improving local air quality in cities: To tree or not to tree?

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ABSTRACT

Vegetation is often quoted as an effective measure to mitigate urban air quality problems. In this work we demonstrate by the use of computer models that the air quality effect of urban vegetation is more complex than implied by such general assumptions. By modelling a variety of real-life examples we show that roadside urban vegetation rather leads to increased pollutant concentrations than it improves the air quality, at least locally. This can be explained by the fact that trees and other types of vegetation reduce the ventilation that is responsible for diluting the traffic emitted pollutants. This aerodynamic effect is shown to be much stronger than the pollutant removal capacity of vegetation. Although the modelling results may be subject to a certain level of uncertainty, our results strongly indicate that the use of urban vegetation for alleviating a local air pollution hotspot is not expected to be a viable solution.

1. Introduction

Because of its adverse effect on human health, air pollution is an environmental problem of major concern. Due to the high traffic density, cities often face increased concentrations of air pollutants in comparison with its surroundings. In order to mitigate these air pollutant problems, the use of urban vegetation is often promoted as an effective measure to reduce concentrations. This measure is based on the underlying argument that trees (and vegetation in general) have the capability of cleaning the air by filtering out the pollutants. Vegetation leaves absorb gaseous pollutants through their stomata, while particles are removed from the air by deposition onto the leaves and the branches. Different studies (Beckett et al., 2000; Freer-Smith et al., 2005; Lovett, 1994) have experimentally assessed the deposition rate at which pollutants are taken up by the urban vegetation. However, Litschke and Kuttler (2008) pointed out that the uncertainty associated to the published values is still large.

Nowak and Crane (2000) have developed a deposition model that is able to estimate the pollutant removal capacity of a so called 'urban forest'. Many studies using this model have reported impressive mass removal estimates for different cities (McPherson et al., 1994; Nowak et al., 2002; Tallis et al., 2011) in order to demonstrate the beneficial effect of urban green on the air quality. However, the resulting decrease in ambient concentrations is much less reported and if so, the effect of the urban forest on the city averaged air quality appears to be rather limited, often not exceeding an improvement of 1–2% (Tallis et al., 2011). In addition, Pataki et al. (2011) recently argued that there is lack of empirical evidence that support the findings of these deposition model simulations thereby concluding that the air quality benefit of urban green may be overestimated.

Although subject to a certain level of uncertainty, this city scale mitigating capacity of urban trees is merely one part of the story. Despite the fact that they effectively remove pollutants from the air, urban trees may under certain circumstances induce a *local* increase of concentrations. It has been shown (Gromke, 2011; Gromke and Ruck, 2007, 2009, 2012; Wania et al., 2011) that trees in urban street canyons obstruct the wind flow thereby reducing the ventilation leading to higher pollutant concentrations. This potentially negative effect of vegetation on the local air quality is much less known amongst policy makers and the broad public. Based upon the general idea that trees clean the air, there still is the misconception that trees are good for air quality in all cases and under all circumstances. Therefore policy makers and urban planners when faced with a local air pollution hotspot, often intuitively reach for trees to alleviate the problem, thereby potentially aggravating the situation.

The study presented in the current paper may be viewed in light of this. The initial goal was to investigate how urban vegetation can be used to improve the local air quality on inner city roads with busy traffic. The study consisted of two parts. In the first part, we conducted a sensitivity analysis where we analysed how different parameters (building geometry, pollutant type, wind conditions and vegetation type, size, position, porosity, filtering capacity)

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influence the impact of roadside vegetation on the local air quality. In the second part, we assessed the effectiveness of 19 different green street designs, designed by urban planners for actual implementation in various cities within Belgium and the Netherlands in order to improve the air quality. Throughout this paper, we will refer to the first part as the *sensitivity analysis* and to the second part as the *case studies*. The entire study was based on computer modelling using the micro-scale model ENVI-met (Bruse and Fleer, 1998).

Although similar studies (Gromke et al., 2008; Buccolieri et al., 2011; Wania et al., 2011) have been published before, from a scientific point of view the current study differs in the following sense:

- **Focus on multiple and traffic related pollutants**. Previous studies are often limited to a single and non-traffic specific pollutant such as PM_{10}.
- **Different types of vegetation**. We do not only consider trees but also study hedges and green barriers.
- **Beyond idealised street canyon geometries**. We also focus on an idealised non-street canyon case (detached building geometry) and study various real life geometries.

The paper is structured as follows: Section 2 describes the general modelling methodology. The sensitivity analysis and the case studies are presented respectively in Section 3 and Section 4. In Section 5 we discuss the results and draw the conclusions.

2. Methodology: the ENVI-met model

All simulations in this work are performed by the ENVI-met model.

2.1. Description of the model

ENVI-met (Bruse and Fleer, 1998) is a three dimensional computational fluid dynamics (CFD) model that is particularly tailored for simulating different urban atmospheric processes such as pollutant dispersion and microclimate effects. The flow solver is based upon the Reynolds averaged Navier–Stokes (RANS) equations and uses an E-ε model for describing the turbulence effects. ENVI-met is freely available from http://www.envi-met.com.

2.1.1. Pollutant dispersion

ENVI-met uses a Eulerian approach to study the dispersion of pollutants. Both gaseous and particulate pollutants can be included. In this work, we have focussed on PM_{10} and the more traffic related pollutants NO_2 and elemental carbon (EC). As elemental carbon mainly resides in the smaller size fractions of the particulate matter (Healy et al., 2012), it is accounted for in ENVI-met as if it were $PM_{0.2}$. For the dispersion of NO_2, we also take into account the chemical reaction between NO_2, NO and O_3 (De Maerschalck et al., 2010). The traffic emissions are in principle represented by line sources. However in order to account for the mixing by the traffic induced turbulence, they are spread out over the entire width of the traffic lane and a height of 1.5 m, see also Figs. 2 and 4.

2.1.2. Vegetation

The exact geometry of vegetation (i.e. leaves and branches) is not explicitly modelled in ENVI-met. The presence of vegetation is represented by introducing additional terms in the governing equations in order to mimic its effect. For the computational cells that coincide with the location of the vegetation, a sink term is added to the momentum equation in the RANS equations in order to account for the flow resistance (or pressure drag) induced by the vegetation. This is analogue to the way porous media are often dealt with in CFD. Also the E-ε equations are equipped with an additional term to simulate the effect of vegetation on the turbulence variables. As explained in Bruse and Fleer (1998) these terms describing the aerodynamic effect of vegetation in ENVI-met only depend on a single plant parameter, i.e. the leaf area density (LAD, total leaf area divided by total volume of vegetation). The filtering capacity of trees is represented by a sink term in the dispersion equation. In ENVI-met this term reads (Bruse, 2007)

$$S = v_d \cdot \mathrm{LAD} \cdot C,$$

where v_d is the deposition speed ([m/s]) and C is the pollutant concentration.

From the above, it can be appreciated that within ENVI-met the effect of vegetation essentially only depends on two parameters: the leaf area density LAD on one side and the deposition speed v_d on the other side. ENVI-met contains further parameterisations to calculate the deposition speed. However, because these calculated values tend to be rather low we will set these parameters equal to values found in the literature (see Section 2.2.2), at least for the particulate pollutants.

2.2. Configuration of the model

2.2.1. Computational domain and mesh

For all simulations presented in this work, the computational domain has been chosen sufficiently large in order for the domain boundaries not to influence the solution. Conform to the best practice guidelines prescribed by Franke et al. (2007) we have chosen to keep clear a distance of 8 H upstream the buildings, a distance of 15 H downstream the buildings, a distance of 8 H in lateral direction, and a height of 10 H above the buildings (where H represents the building height). For the computational mesh we use a non-uniform Cartesian grid with a resolution of 0.5 m inside the canyon which is sufficiently fine to ensure the minimally recommended amount of 10 × 10 cells in the canyon cross-section (Franke et al., 2007). The grid size increases towards the boundaries of the domain with the expansion factor not exceeding the value of 1.3. A grid sensitivity analysis has been performed for the street canyon geometry out of Section 3 (the reference case without vegetation and with perpendicular wind). Next to the fine resolution of 0.5 m, simulations with a maximal resolution of 1 m (medium grid) and 2 m (coarse grid) have been assessed. The results in Fig. 1 show that the computed wind speed inside the canyon is independent of the grid size. For the pollutant concentration inside the canyon, we see that the results on the coarse grid differ from the results on the fine grid. The correlation between the fine and medium grid is remarkably better, although not perfect for the highest concentrations which occur close to the pollutant source central in the canyon. Because the focus in this work will be on the concentration at the footpaths, and since the grid dependence in this area is minimal for the fine and medium grid (see Fig. 1), we believe a resolution of 0.5 m is justified for all simulations in this study, especially taking into account the overall uncertainty of the modelling approach as discussed in Section 2.3.

2.2.2. Boundary conditions and parameter values

In ENVI-met, the profile of the flow variables at the inflow boundary is calculated by the built-in one-dimensional model. This 1D model requires the wind speed at a height of 10 m and for all simulations in this study, this has been set to 3 m/s. Table 1 contains an overview of the default values of a list of other parameters that are of importance for this study. The chosen default values for the parameters LAD and v_d are based on typical values published in the literature. The range of reported particle deposition speeds v_d is large (Beckett et al., 2000; Freer-

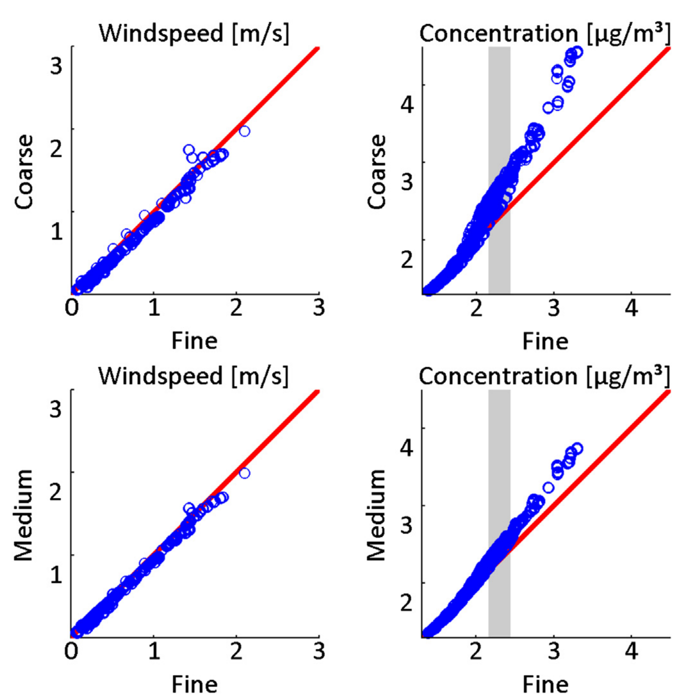

Fig. 1. Comparison of results (Left: Wind speed – Right: Concentration of Elemental Carbon) depending on the resolution of the grid (Top: Coarse versus Fine – Bottom: Medium versus Fine). Depicted are all the values inside the canyon, sampled at the resolution of the coarse grid. The shaded area corresponds with the range of the EC concentrations calculated at the footpaths.

Table 1
Overview of the default values of the most important parameters needed to configure the ENVI-met model.

Parameter type	Parameter name		Sensitivity analysis (SA) or case study (CS)	Value
Meteo	Windspeed at 10 m		SA + CS	3 m/s
Vegetation	Leaf area density (LAD)	Tree	SA + CS	0.7 m^2/m^3
		Hedge	SA + CS	2 m^2/m^3
		Green barrier (vegetation cover)	SA + CS	2 m^2/m^3
	Deposition speed v_d	NO_2	SA + CS	Calculated by ENVI-met
		PM_{10}	SA + CS	2 mm/s
		EC	SA + CS	0.5 mm/s
Pollutant	Line source emissions	NO_2	SA	51 μg/(m*s)
		NO	SA	284 μg/(m*s)
		PM_{10}	SA	27 μg/(m*s)
		EC	SA	10 μg/(m*s)
		NO_x, PM_{10}, EC	CS	Case dependent
	Background concentration	NO_2	SA + CS	21 $\mu g/m^3$
		NO	SA + CS	11 $\mu g/m^3$
		O_3	SA + CS	43 $\mu g/m^3$
		PM_{10}	SA + CS	24 $\mu g/m^3$
		EC	SA + CS	1.3 $\mu g/m^3$

Smith et al., 2005; Lovett, 1994; Petroff and Zhang, 2010), but both for PM_{10} and EC we have selected values that can be considered representative according to the values presented in the review article of Litschke and Kuttler (2008). The deposition speeds are assumed independent of the vegetation type. In Section 3.2.4, we investigate the influence of varying the value of v_d for a hedge. For the leaf area density (LAD) of trees we have chosen a default value of 0.7 m^2/m^3. Taking into account the three-dimensional tree geometry in ENVI-met, this corresponds to a leaf area index (LAI, m^2 leaf area per m^2 projected ground area of the tree crown) of 4.2. This LAI value is equal to the average LAI of urban trees as reported in Nowak et al. (2002). The chosen LAD value of 0.7 m^2/m^3 is also consistent with the values as presented in Lalic and Mihailovic (2004) and Stadt and Lieffers (2000), although they might be more representative for forest canopies. As hedges are generally denser than trees, we have set the default value of LAD for hedges equal to 2 m^2/m^3 and in Section 3.2.4 we investigate the effect of increasing this parameter. For the vegetation cover of green barriers, we adopt an identical LAD of 2 m^2/m^3. A green barrier is defined as a solid (impermeable) screen covered with hedge-like vegetation at both sides. The line source emissions for the sensitivity analysis are representative for a traffic intensity of 1600 vehicles/hour and are calculated based upon the standard Dutch emission factors for 2012. For EC, we have assumed the emission factors to be 66% of the emission factors of $PM_{2.5}$ following Lefebvre et al. (2011). For the case studies presented in Section 4, case specific emissions will be used based upon the corresponding traffic intensity. The background concentrations are set to typical values for The Netherlands and Belgium and are identical for both the sensitivity analysis and the case studies.

2.3. Validation and uncertainty of the model

A model, as implied by the word, is merely a model of reality. As such, its use induces a certain level of uncertainty. Previous studies have elaborated on the validation of the ENVI-met model, see e.g. Nikolova et al. (2011). In a more similar context of the air quality impact of vegetation, De Maerschalck et al. (2008) showed a good agreement between measurement data and ENVI-met results. However, this study considered the impact of a green barrier along a motorway which cannot be seen as completely analogue to the scenarios studied in this work. Therefore one could argue that additional validation of the ENVI-met model is needed in order to validate the results presented in this work. The problem is that no suitable validation dataset is available for comparison. To our best knowledge, no real life measurement campaign that studies the effect of vegetation on the local air quality in an urban environment has been published (thereby neglecting the wind tunnel study of Gromke and Ruck (2007, 2009, 2012) which can be considered as a different type of model). This of course introduces a certain level of uncertainty to the results presented in this work. In order to handle this uncertainty, it is important to interpret the results of the model simulations in an appropriate way. As the uncertainty associated to the value of a pollutant concentration at a specific location for a certain scenario is expected to be higher, we will primarily focus on the general recurring trends that show up from the multitude of studied scenarios rather than on individual results. By doing so, we believe that the modelling results presented in this work do have a valuable role: by combining the best available knowledge available within the modelling community, we are able to make a fair prediction of what we expect to be the effect of green on the local air quality, at least from a quantitative point of view. However, further studies to support and confirm our findings are necessary.

3. Sensitivity analysis

3.1. Set-up

The goal of the sensitivity analysis was to investigate how different parameters influence the impact of vegetation on the local air quality. Four different parameters were varied: the geometry of the build environment, the type of pollutant, the meteorological conditions and – most importantly – the vegetation. In terms of geometry two different kinds of idealised street geometries where investigated: a street canyon geometry and a detached housing geometry. An overview of both geometries is graphically represented in Fig. 2. The chosen dimensions are considered to be representative for the corresponding geometry types in Belgium and the Netherlands and the pollutants NO_2, PM_{10} and EC will be investigated. For the meteorology we will only vary the wind direction (the wind speed is fixed at 3 m/s, see Table 1), limiting ourselves to two cases: wind perpendicular to the street (90°) and an oblique wind direction (45°), see Fig. 1. The most important parameter to be varied is the vegetation: this includes different types of vegetation (trees, hedges, green barriers) and variations in height, location, porosity and filtering capacity. An overview of all 17 vegetation scenarios is depicted in Appendix A.

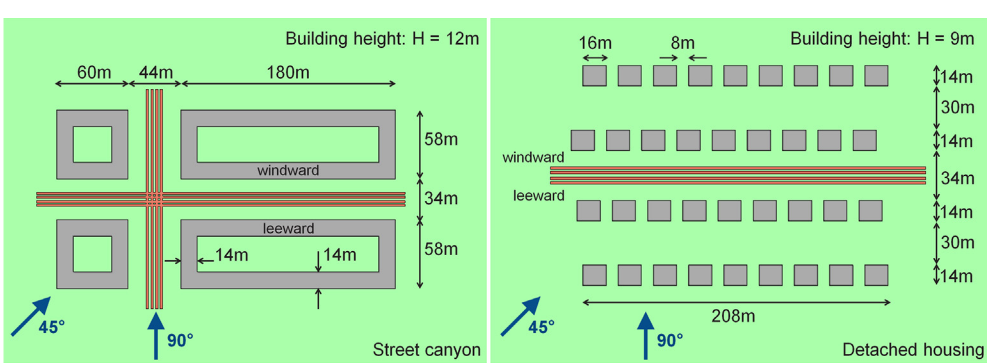

Fig. 2. Schematic overview of the dimensions of the two types of building geometries (Street canyon, left; Detached housing, right) studied in the sensitivity analysis. The two considered wind directions are indicated in blue. Note: the computational domain is larger than the depicted area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Not all vegetation configurations have been investigated for each street geometry, but in total 144 different scenarios were computed by the ENVI-met model (see Fig. 3 for an overview of all scenarios).

3.2. Results

For the results we consider the mean pollutant concentration at the footpath, averaging the concentrations over the entire width of the footpath (2.5 m) and over a length of 120 m at a height of 1.5 m (breathing height). We make a distinction between the footpath on the leeward side and the footpath on the windward side of the street, see Fig. 2.

3.2.1. Global overview

An overview of the results of all studied scenarios is depicted in Fig. 3 where the relative difference in pollutant concentration due to the presence of the vegetation is shown. A positive difference represents an increased concentration and hence, a deteriorated air quality. The negative numbers on the other hand indicate that the vegetation causes an improvement in air quality. From the figures, it can clearly be seen that the results are not unanimously showing the allegedly beneficial effect of urban vegetation. On the contrary it is only the use of high impermeable green barriers that lead to a significant improvement in air quality. Below, the results will be discussed in more detail.

3.2.2. Influence of pollutant, geometry and wind direction

The results in Fig. 3 show that trees have much less influence on the ambient PM_{10} concentrations than on the NO_2 and EC concentrations, mainly because the contribution of the PM_{10} traffic emissions is relatively low compared to the background concentration. Vegetation will primarily affect the concentrations of traffic related pollutants such as NO_2 and EC.

The general effect of vegetation is similar for both geometry types. A difference is that for the detached building case we see little impact at the leeward side. This can be explained by the fact that the traffic emitted pollutants are mainly transported downstream towards the footpath at the windward side (there is no recirculating vortex as in the street canyon case). This not only means that the vegetation will be of little influence for the leeward side, but also that the observed effect is less relevant because the pollutant concentrations will be quite low in absolute numbers.

In terms of wind direction, we see for the detached building case that the air quality effect of a certain vegetation scenario turns out to be similar for both wind directions, at least qualitatively. For the street canyon geometry, we see a little more difference between both wind directions (see also Section 3.2.4).

In the remainder of this section we will focus on the variations in the vegetation. Due to the similarities observed above, we will do this analysis independent of the geometry type and, where valid, wind direction. The described effect will particularly apply for the traffic related pollutants NO_2 and EC.

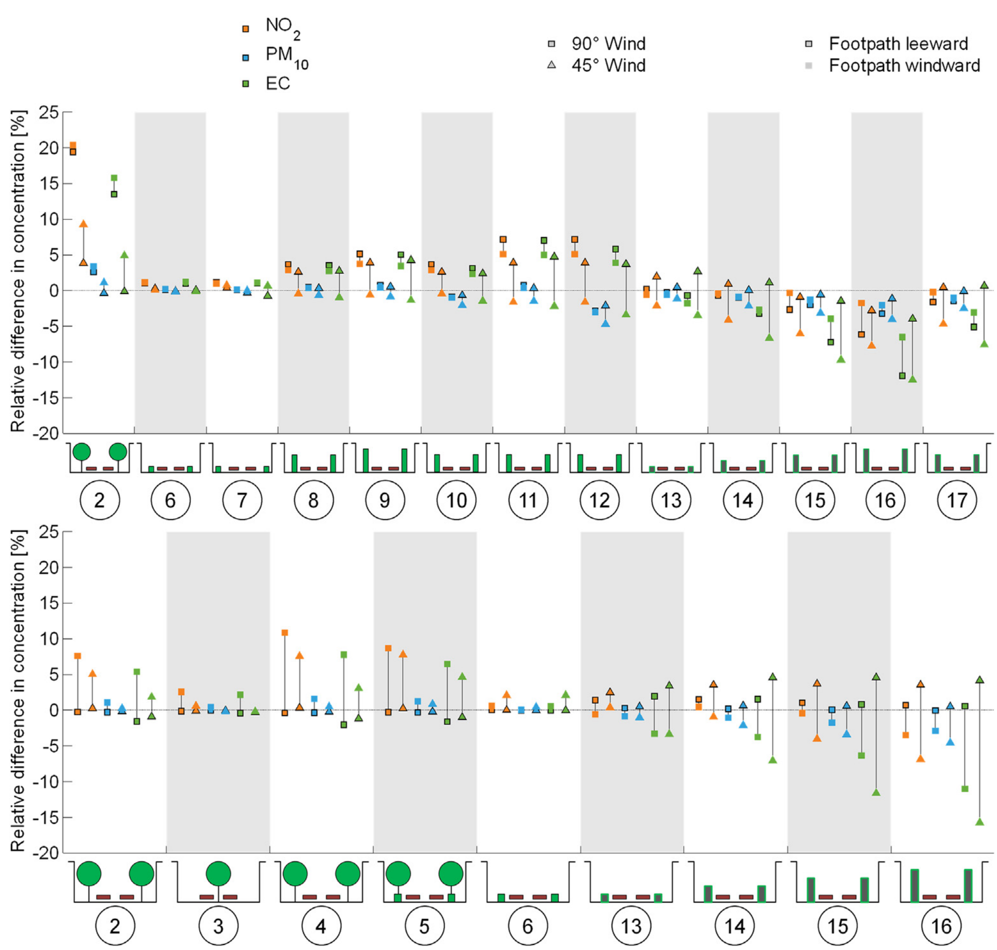

Fig. 3. Overview of the results of all scenarios studied in the sensitivity analysis: Relative difference in concentration at the footpath (1.5 m height) with respect to the reference case (no vegetation). Top: street canyon geometry. Bottom: detached housing geometry.

3.2.3. Influence of vegetation type (tree/hedge/green barrier)

From Fig. 3, it appears that trees significantly increase the pollutant concentrations. Also hedges have the tendency to deteriorate the air quality. Only green barriers seem to have the capability to improve the air quality at the footpath. Hereby we would like to note that this can mainly be attributed to the impermeable core of the green barrier. In fact, simulations with a bare solid screen (without the vegetation cover) yielded quasi identical results.

In order to appreciate these observations, one should consider the underlying mechanisms. For trees it is the deceleration of the flow (see Fig. 4, top left) that causes the pollutants to be highly concentrated at the point of emission as there is less air available for dilution. These higher concentrations will be transported to the footpath, as depicted in Fig. 4 (top right). This reduced ventilation by trees in street canyons has been observed as well by Gromke and Ruck (2007, 2009, 2012).

Hedges and green barriers also lower the wind speed on street level. However, the impermeable green barriers effectively shield the footpath from the elevated concentrations at the traffic lanes, leading to lower concentrations at the footpath with respect to the situation without any vegetation at all, see Fig. 4 (bottom right). The pollutants are mainly transported vertically in this case. Simulations with an interrupted green barrier (Vegetation scenario 17) suggest that gaps do not reverse the beneficial effect of the barrier.

Although hedges have a similar shape as green barriers, their effect is notably different: the permeability allows the horizontal transport of pollutants throughout the hedge in the direction of the footpaths. And because of the higher concentrations at the traffic lanes (because of the reduced wind speed), the concentrations at the footpaths will be higher than without the hedges, see Fig. 4 (bottom left).

This also indicates that it is the aerodynamic effect of the vegetation rather than the filtering capacity that prescribes the impact on the local air quality.

3.2.4. Influence of variations in vegetation

3.2.4.1. Height (hedge/green barrier). Hedges and green barriers have negligible effect as long as they are small (say below 1 m). For increasing height, we see two opposing general trends: a higher green barrier leads to lower concentrations at the footpath (due to better shielding), while a higher hedge increases the pollutant concentrations (due to less ventilation). This is also depicted in Fig. 5. Two particularities can be observed for the oblique wind direction of 45°: 1) Low green barriers do have a negative effect on the air quality at the leeward side of the canyon. 2) Higher hedges do not increase concentrations at the windward side of the canyon. We deliberately do not want to attach too much importance to these individual cases. As indicated in Section 2.3, the uncertainty of the CFD results of a single scenario is relatively high such that a detailed analysis of each deviating case in our view is of less relevance as compared to the general conclusions stated above.

3.2.4.2. Planting distance (tree). When plotting the results of the different tree-only scenarios in function of the number of trees (see Fig. 6), our results in general indicate that the less trees, the lower the pollutant concentrations. The negligible effect on the leeward side of the road can be attributed to the fact that for the detached housing geometry, there is not much pollutant transport upstream (see also Section 3.2.2).

3.2.4.3. Porosity. When increasing the LAD of a 3 m high hedge from 2 m^2/m^3 (Vegetation scenario 8) to 5 m^2/m^3 (Vegetation scenario 11), we see in Fig. 3 that the results become more pronounced. From a qualitative point of view, the effect of the hedge does not appear to reverse due to this substantially lower porosity.

3.2.4.4. Filtering capacity. Simulations with a five times higher deposition speed than the default value (see Table 1) for a 3 m high hedge show no significant difference in the results (Vegetation scenario 8 vs. 10). This is in line with a previous ENVI-met study (CROW, 2012) where it was found that the value of the deposition speed is hardly affecting the air quality impact of trees in a street canyon. This also corroborates our earlier statement that for urban vegetation along inner city roads, it is mainly the aerodynamic effect that determines the effect on the air quality and not the pollutant removal capacity.

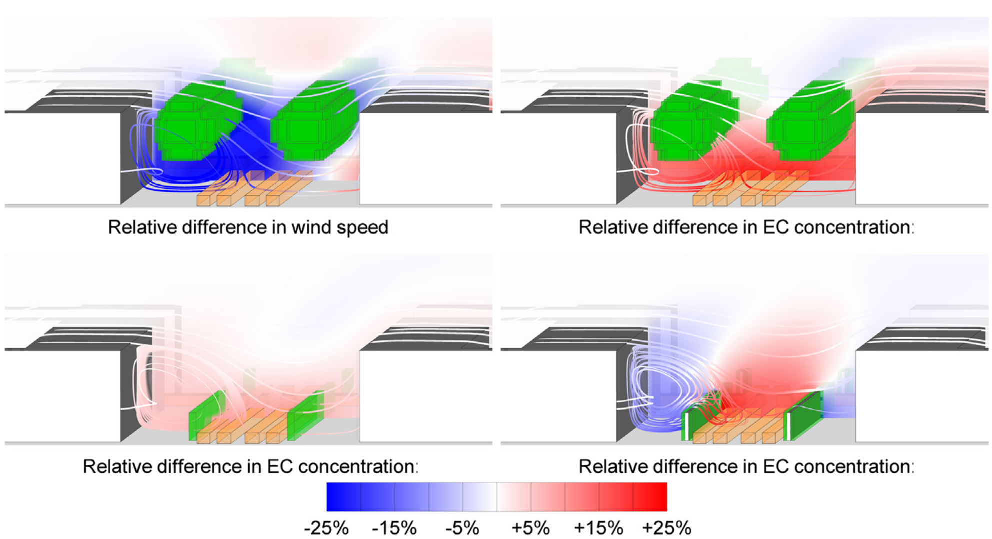

Fig. 4. Visualisation of selected ENVI-met results for the street canyon geometry. The wind direction is 90° (from left to right). The ribbons correspond to streamlines and the orange bars in the centre to the location of the traffic emissions. Top left: relative difference in wind speed for the tree scenario (Vegetation scenario 2). Top right: relative difference in EC concentration for the tree scenario (Vegetation scenario 2). Bottom left: relative difference in EC concentration for the 4 m high hedge (Vegetation scenario 9). Bottom right: relative difference in EC concentration for the 4 m high green barrier (Vegetation scenario 16). All relative differences are with respect to the reference case without vegetation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

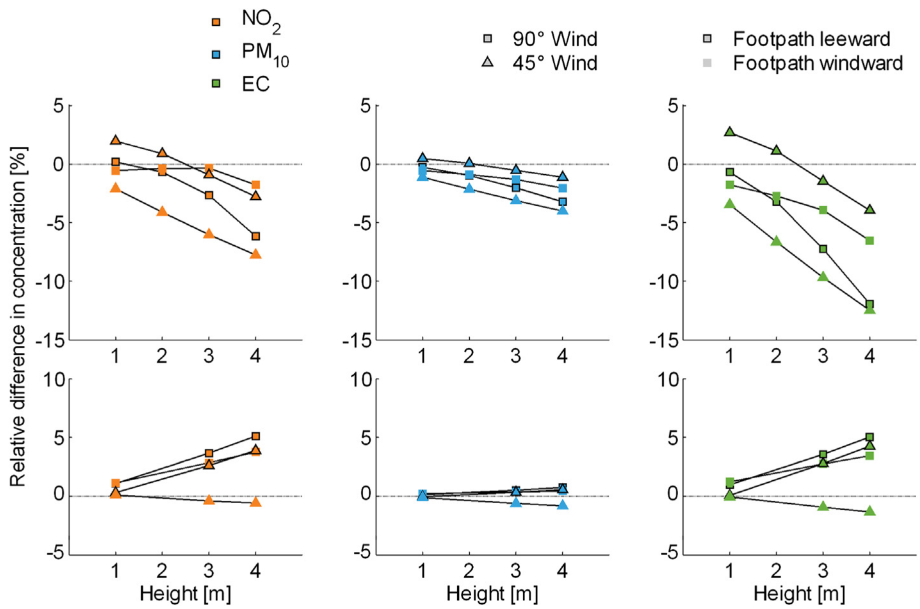

Fig. 5. Influence of height: relative difference in concentration (with respect to reference case without vegetation) in function of the green barrier (top row) and hedge (bottom row) height for the street canyon geometry. Results of the 1, 2, 3, 4 m high green barrier (top row) respectively correspond with vegetation scenarios 13, 14, 15, 16. Results of the 1, 2, 4 m high hedge (bottom row) respectively correspond with vegetation scenarios 6, 8, 9. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Case studies

4.1. Set-up

In the second part of this study, we have assessed the effectiveness of 19 different real-life urban vegetation designs. These designs have been made by city planners in an attempt to improve the local air quality at the various streets. All 19 designs are meant for actual implementation and the streets are all located in Belgium and The Netherlands. Appendix B contains an overview of the 19 different designs. For each case, two different scenarios have been assessed: one with the vegetation and one without. Only a single wind direction of 90° (perpendicular to the street) has been considered.

4.2. Results

Fig. 7 summarises all results of the cases studies. It turns out that out of the 19 cases, we can observe a distinct air quality improvement for only one design (case 4). This design consisted out of 4 m high impermeable green barriers between the traffic lanes and the footpath. In almost all other designs, trees were chosen. Just as in the sensitivity analysis, the ENVI-met results show that roadside urban trees have a detrimental effect on the local air quality. The results also show that the higher the surrounding buildings (i.e. the deeper the canyon; case 7, 8, 9, 10, 16), the bigger the negative impact of urban trees. This adds to the disadvantage since these are the cases that yield the highest concentrations of pollutant even without the trees. The peak result of case 10 can be attributed to a combination of densely planted trees together with hedges, a narrow street, high buildings and high traffic emissions. The results in Fig. 7 also confirm that for street canyons, both sides of the street are affected by the presence of vegetation while for more open building configurations, the effect of vegetation is mainly limited to the windward side of the street. In case there are practically no buildings close to the road (case 6, 17, 18, 19), vegetation still has a negative impact on the concentrations downstream the road. As long as the road is within the aerodynamic zone of influence of the vegetation, concentrations are expected to go up due to

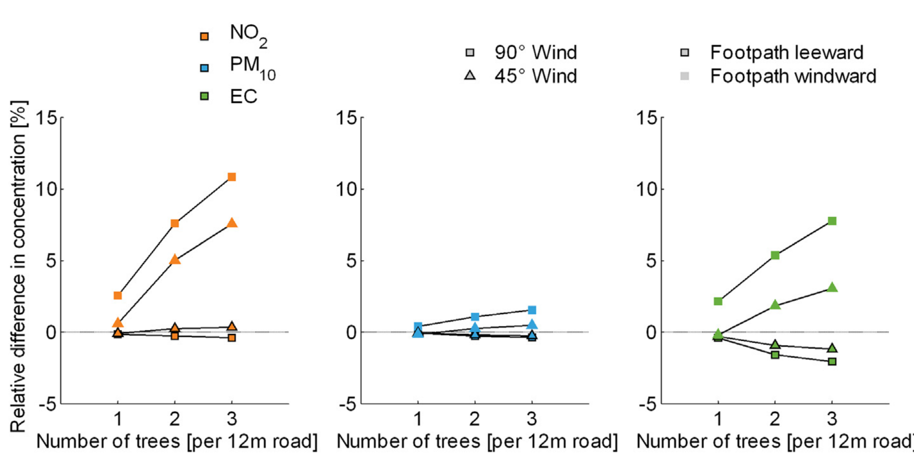

Fig. 6. Influence of tree planting distance: relative difference in concentration (with respect to reference case without vegetation) in function of the number of trees per 12 m road distance for the detached housing geometry. Results for the case with 1, 2, 3 trees per 12 m road respectively correspond to vegetation scenario 2, 3, 4.

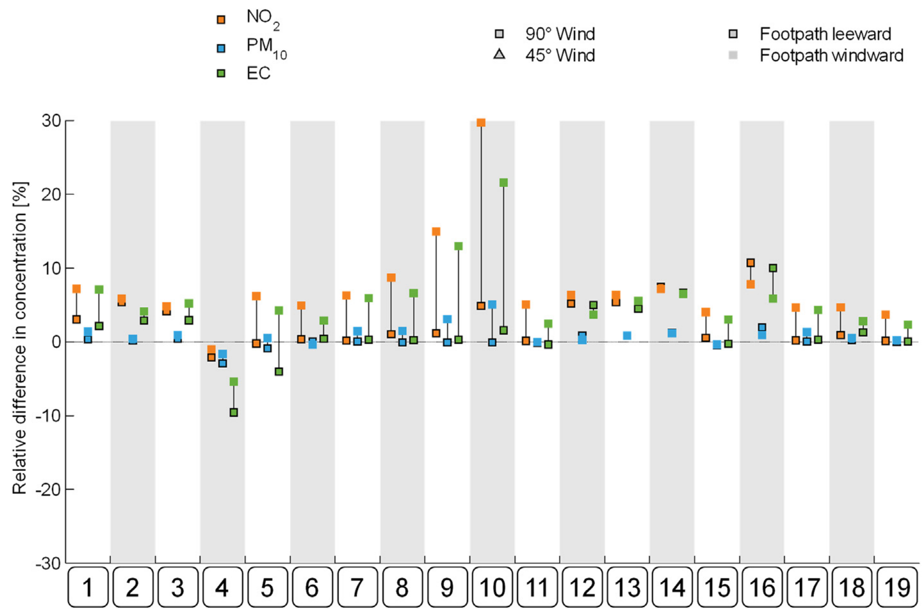

Fig. 7. Overview of the results of all green street designs studied in the sensitivity analysis: Relative difference in concentration at the footpath (1.5 m height) with respect to a reference case without vegetation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the reduced wind speed. But because the concentrations anyhow are lower for these open cases, the adverse effect can be deemed less problematic than for the urban configurations (Fig. 8).

5. Discussion, conclusion and recommendations

5.1. Relevance for city planners & policy makers

Inspired by questions from city planners, the initial goal of this study was to investigate how roadside urban vegetation can be used to improve the local air quality. The results presented in this work indicate that this appears to be very hard to accomplish. Only rather high (3–4 m) impermeable screens lead to a significant reduction in concentrations at the footpath. However it is questionable whether such high screens are realistic and desirable in practice. More common options such as trees and hedges on the other hand appear to have an opposite effect as originally intended. The results in this work show that especially trees may lead to significantly higher concentrations, in particular for traffic related pollutants such as NO_2 and EC. This can be explained by the fact that urban vegetation obstructs the wind flow, thereby reducing the ventilation that is responsible for diluting the pollutants. This aerodynamic effect seems to outweigh the filtering capacity of vegetation. Although there may be some level of uncertainty associated to these modelling results our analysis confirm the earlier findings of e.g. Gromke and Ruck (2007, 2009, 2012). However, there is still need for empirical evidence (see also Section 2.3) to support the results of this and similar previous work.

The general observation that urban vegetation has a detrimental effect on the local air quality also indicates that the initial question may be wrong. There is need for a paradigm shift: rather than asking “How to use urban vegetation to improve local air quality”, our results suggest that urban planners and policy makers should better start from the question “How can urban vegetation be used without significantly deteriorating the local air quality”. From the results presented here, we would advise to use options that have a limited impact on the air flow, i.e. low hedges and isolated trees every here and there. From a local air quality point of view, dense rows of trees are avoidable, especially in street canyons with busy traffic.

It is of great importance to take into account the broader context of these results and conclusions. The scope of our work was only limited to the role of *roadside urban* vegetation on the *local* air quality. The fact that roadside trees negatively affect the local air quality does not mean that trees in urban backyards, urban parks or traffic free streets have a similar effect. On the contrary, the effect of roadside urban trees on the *city-averaged* air quality is expected to be positive (Tallis et al., 2011). Next to air quality, urban vegetation plays a multitude of different roles in the urban environment: they provide shade, absorb and store carbon dioxide, mitigate the urban heat island effect, affect noise hindrance, enrich the urban biodiversity, etc. (Bolund and Hunhammar, 1999). In addition, trees and urban vegetation in general do have an aesthetical and emotional value. Taking this into account, the argument of local air quality does not necessarily need to be a reason not to plant roadside urban vegetation. However our results suggest that it is scientifically not correct to plant roadside trees to improve the local air quality.

5.2. Green paradox

There are a variety of different scales to consider when studying the effect of urban vegetation on the urban air quality. In this work, we have focussed on the local (street level) air quality, but many previous studies have considered the urban scale (i.e. city averaged) air quality. Depending on the scale, the conclusions with respect to the use of trees appear to oppose each other. As discussed above, for optimal *local* air quality, one could argue that urban trees should be planted far away from the pollutant source (in order not to hamper the ventilation). However for an optimal city averaged air quality, Tallis et al. (2011) recommend planting trees as close as possible to the pollutant sources as pollutant removal by trees increases with pollutant concentration. Although the above recommendations are paradoxical, the underlying observations concerning the air pollutant concentrations do not necessarily oppose each other. Urban trees truly do have an opposed effect on different scales. In order to better understand the effect of urban trees on the "air quality" (independent of the scale), and subsequently define proper mitigation strategies, there is the need for a multi-scale approach combining both scales in a single analysis.

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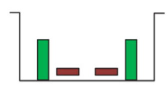
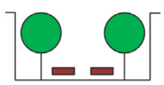
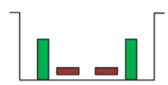
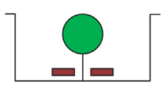
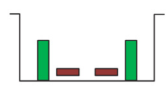
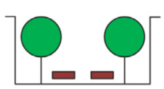
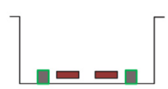
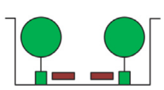
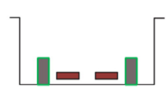
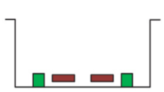
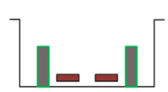
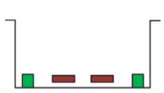
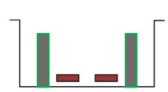
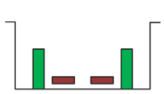
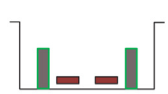
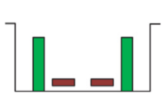
Appendix A. Vegetation scenarios for the sensitivity analysis

Table 2
Overview of the 17 different vegetation scenarios studies in the sensitivity analysis. Unless mentioned otherwise, LAD and v_d are set to the values as given in Table 1.

1		**Reference case** No vegetation	10		**3m high hedge** Hedge height: 3m Hedge width: 1m $v_d(PM_{10})$=10 mm/s
2		**Double tree row** Tree height: 15m Crown diameter: 8m Crown base height: 6m Tree spacing: 12m	11		**3m high hedge** Hedge height: 3m Hedge width: 1m LAD=5 m^2/m^3
3		**Single tree row** Tree height: 15m Crown diameter: 8m Crown base height: 6m Tree spacing: 12m	12		**3m high hedge** Hedge height: 3m Hedge width: 1m $v_d(PM_{10})$=10mm/s LAD=5 m^2/m^3
4		**Double tree row** Tree height: 15m Crown diameter: 8m Crown base height: 6m *Tree spacing: 8m*	13		**1m high green barrier** Barrier height: 1m Barrier width: 1m
5		**Double tree row + hedge** Tree height: 15m Crown diameter: 8m Crown base height: 6m Tree spacing: 12m Hedge height: 1m Hedge width: 1m	14		**2m high greenbarrier** Barrier height: 2m Barrier width: 1m
6		**1m high hedge** Hedge height: 1m Hedge width: 1m	15		**3m high green barrier** Barrier height: 3m Barrier width: 1m
7		**1m high hedge** Hedge height: 1m Hedge width: 1m 3m from road	16		**4m high green barrier** Barrier height: 4m Barrier width: 1m
8		**3m high hedge** Hedge height: 3m Hedge width: 1m	17		**3m high green barrier** Barrier height: 3m Barrier width: 1m Interrupted (6m gap every 32m)
9		**4m high hedge** Hedge height: 4m Hedge width: 1m			

Appendix B. Green street designs for the case studies

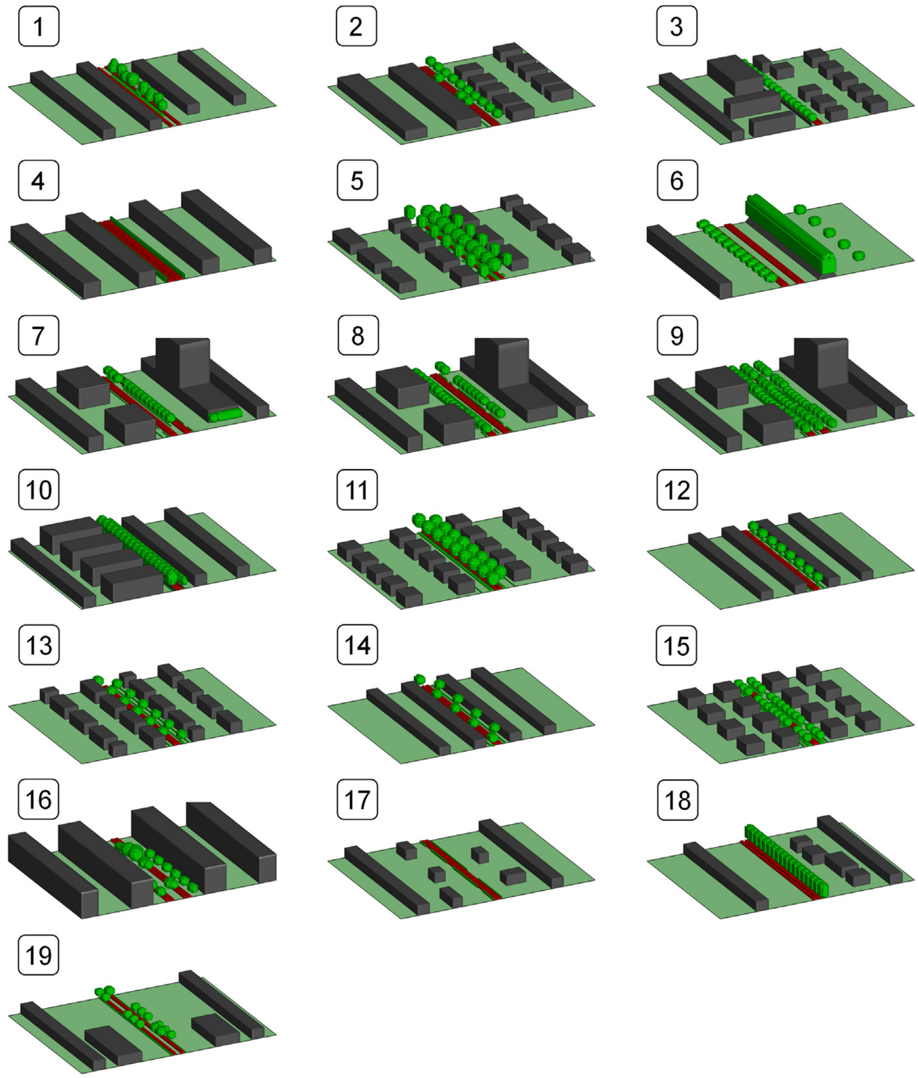


Fig. 8. Graphical impression of the ENVI-met geometry of the 19 different green street designs considered in the case studies. Note: the computational domain is larger than the depicted area.

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