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THE UNIVERSITY OF BRITISH COLUMBIA

Simulating the effect of adding vegetative buffers around poultry barns on mean wind and concentrations of PM10

Daryll Pauls[1] and Andreas Christen[2]

[1] Summer Student Research Assistant, Atmospheric Science Program,
University of British Columbia, Vancouver, Canada

[2] Assistant Professor, Department of Geography / Atmospheric Science Program,
University of British Columbia, Vancouver, Canada
(Corresponding author)
andreas.christen@ubc.ca

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S. Bittman
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Abstract

Controlling emissions of particulate matter from poultry facilities is desirable to mitigate negative impacts of emissions on natural resources and human health. A potential emission management strategy is to enhance deposition on ground and vegetation inside the property line and consequently reduce dispersion to neighbouring properties. This can be possibly achieved though planting of vegetative buffers on and around poultry facilities. This report evaluates and applies a simple building-resolving flow and dispersion model to determine the effects of adding vegetation buffers around poultry barns to mitigate particulate matter (PM10) emissions leaving the property line. Different buffer layouts were studied and their potential on reducing wind, increasing concentration and deposition of PM10 was evaluated. Two different buffer layout scenarios were tested - a perimeter planting and an infill of the alleyway between barns. Sensitivities to plan area density, leaf area density and height of the vegetative buffer are quantified in terms of decreasing wind and increasing concentrations of PM10 at screen level. The model estimates that deposition on buffer vegetation was minor, and only about ~10% of the emitted PM10 could be removed by dry deposition. In none of the modeled scenarios, total PM10 leaving the property was significantly reduced. The model does not include effects of wet deposition and impactation, which could further enhance removal.

Keywords

Agriculture, Deposition, Dispersion, Micrometeorology, Particulate matter, PM10, Poultry barns, Tree planting, Vegetative buffers, Wind.

1. INTRODUCTION

1.1. Objective of research

Controlling emissions of gases, particulate matter and associated odour from poultry facilities is desirable to mitigate negative impacts of those emissions on natural resources and human health. In addition, respiratory virus transmission between facilities via air is an additional concern in areas with a high density of facilities, such as in the Lower Fraser Valley (BC, Canada). A reduction of emission source strength, specifically of particular matter, will reduce the risk of cross contamination and reduce air pollution.

There are two fundamentally different options to reduce the total mass of particulate matter leaving a facility: **(1)** Reducing the mass of particulate matter leaving the barn buildings. This can be achieved through management and technical solutions, such as controlling venting and electrostatic precipitators. This should be the primary focus of any mitigation option. **(2)** To enhance deposition on ground and vegetation inside the property line and consequently reduce dispersion to neighbouring properties. The second option might be achieved for example though planting of vegetative buffers on and around poultry facilities. This report will focus on the second option, specifically the effect of vegetative buffers on wind and dispersion characteristics. However the report clearly acknowledges the potential of strategy 1.

The objective of this report is to:

- Evaluate the applicability of a building-resolving flow and dispersion model (ENVI-met 3.1) to determine the effects of adding vegetation buffers on the wind field, the dispersion of particulate matter and the deposition of particulate matter on vegetation and ground within the property line.
- Apply the model to study different buffer layouts and estimate their potential on reducing particulate matter emissions.

Vegetative buffers further have shading / sheltering effects that might reduce ventilation and heating demand of facilities. Those secondary benefits are not investigated in this study.

1.2. How does a vegetative buffer work?

Deposition is the physical process of particulate matter collecting or depositing on a solid surface, and thus decreasing the particle concentration in the ambient air. Deposition can be *wet deposition* or *dry deposition*. Wet deposition occurs when atmospheric hydrometeors (rain, snow, hail, cloud droplet etc.) intersect with particles thus removing them from the atmosphere. It could be artificially promoted by sprinklers etc. However, wet deposition is not considered in this study.

Dry deposition may either be due to *gravitational sedimentation* on horizontal surfaces, or *impaction on objects* such as leaves. Gravitational sedimentation is the process of particles moving towards a surface due to the effects of gravity. The downward flux due to gravitational settling can be quantified by the settling velocity v_s, which depends on the particle density, diameter and its aerodynamic properties (drag coefficient) and the aerodynamic and laminar boundary layer resistances of the surface. Settling velocities for medium-size particles (1 to 100 μm) are generally quite small and in the order of 0.2 m h^{-1}. The total flux by sedimentation depends on the concentration near the surface. A higher concentration in the property will cause (at same setting velocity and resisntances) a higher deposition flux within the property. Interception occurs when small particles, advected with the wind collide with an obstacle, such as vegetation, a building, or the surface. The removal through impaction will increase when for example liquid droplets are introduced on the surface of the leaf, or electric charges are present. Interception is increased with increasing concentrations and increasing leaf area density.

Hence, as a first principle, a vegetative buffer should provide ample leaf area at locations where concentrations are high so the leaves can increase impaction. As a second principle, controlling flow and turbulence around a barn by strategically planting a buffer will further affect the concentration of particles inside the property and close to the buffer. The secondary goal of the filter is therefore also to *reduce wind* and to *reduce turbulent mixing* and consequently to *increase concentrations* inside the property. There are a few counter-acting effects such as that impaction depends on the resistance of the laminar boundary layer, which will in turn increase with decreasing wind.

Although increasing the near-surface concentrations will worsen the air pollution in the near-field (i.e. on the property), it will decrease total emissions leaving the property line. Appropriate measures have to be implemented to ensure that the decreased air quality does not affect facility operations i.e. air intake for the barns should be placed upwind and residential buildings should be well separated from the barns.

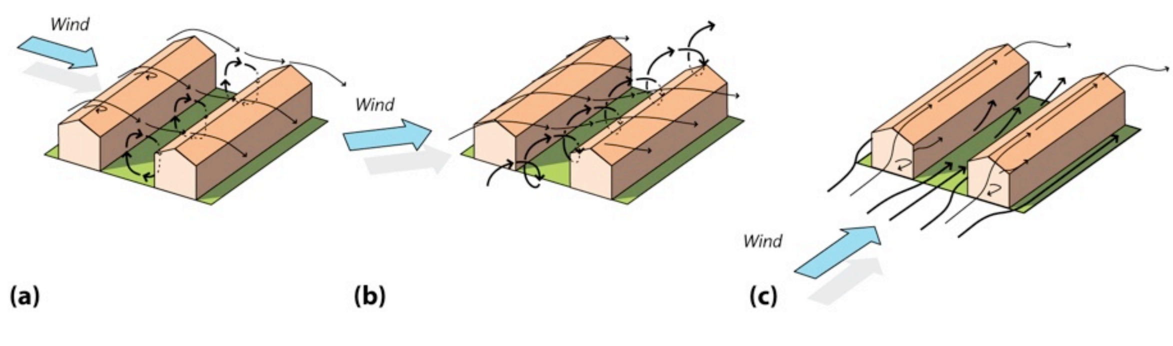


Figure 1 - Postulated flow types for wind approaching a two-barn layout with changing direction of the approaching flow. Flow perpendicular to the gables causes a vortex (a), flow oblique to the gables causes a corkscrew flow pattern (b), while wind aligned with wind aligned with the gables will result in jetting (c).

1.3. Flow around barn buildings

Figure 1 shows a typical barn layout as found in the Lower Fraser Valley. Particulate matter is emitted from the barns towards the open space in between the two barns, at about a height of 1.5 m. We will refer to this space as 'alleyway'. It is aerodynamically comparable to a channel between the rigid barns, or similar to a 'street alleyway' in an urban setting.

It is expected that flow perpendicular to the barns (Figure 1a) will cause air in the alleyway to partially recirculate and form vortices. With typical dimensions of spacing (5-12m) vs. height of barns (5m), we can expect either a 'skimming flow régime' or a 'wake interference flow régime'. For flow oblique to the barns (Figure 1b) the flow will follow a corkscrew pattern. In both cases the flow will be associated with substantial vertical velocities, mixing lower and upper part of the alleyway efficiently. When the ambient wind is in alignment with the barns, the flow will accelerate and lift up (Figure 1c).

Figure 2 shows the effect of adding a buffer on the dispersion of particulate matter. Adding a buffer (right) will decrease wind near the filter, increasing concentrations near to the barns, and part of the aerosol mass will be removed by impaction on leaves. However the buffer will also lift the polluted air upwards where it mixes more efficiently. The current report will identify controls and quantify potential effects.

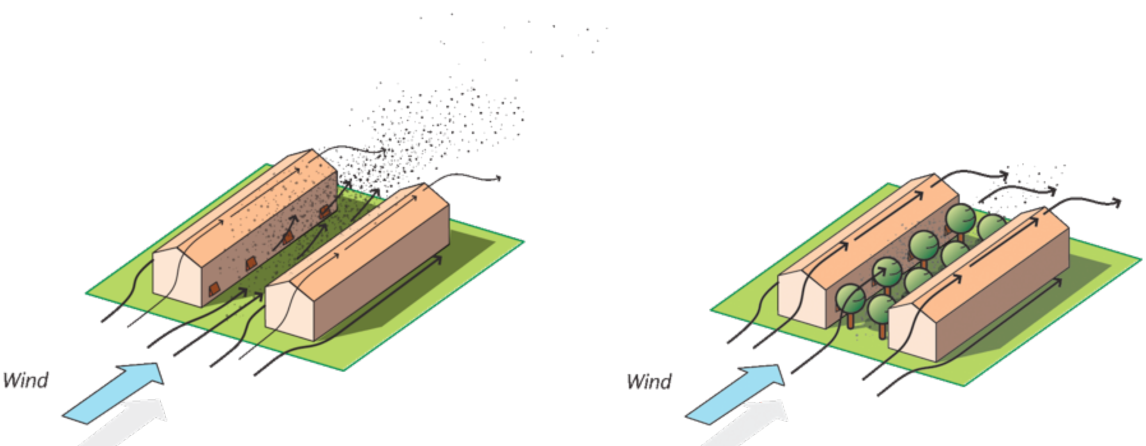


Figure 2 - Postulated effect of a vegetated buffer on wind and concentrations.

2. MATERIALS AND METHODS

2.1. Model description

The program ENVI-met (Bruse and Flehr, 1998) Version 3.1, BETA V[1] was used in this study to model the detailed wind field around barns with and without vegetative buffers. ENVI-met is a 3-dimensional computational fluid mechanics modeling program that is designed to simulate interactions between surfaces, buildings and plants, and the air flow which may contain both gaseous or particulate emissions. Using the fundamental fluid and thermodynamic equations, ENVI-met is solving equations in a rectangular grid to determine mean flow and turbulence in in each grid-cell. It further considers exchange processes of radiation, heat and vapour at the ground surface, walls and roofs.

ENVI-met is using an editor that makes use of map overlays, and a construction toolbox that contains many different types of plants, buildings, and soils, it is relatively easy and practical to approximate "real world" landscapes at scales between about 10 and 1000 m. The grid sizes are variable between 0.5 meters to 10 m, to allow the modeller to choose between higher resolution and less model area, or lower resolution and a larger model area. In addition, plants and trees are more than just porous blocks in ENVI-met, they actually incorporate the uptake and emissions of chemicals at different heights of the vegetation, as well as the output into both the soil and atmosphere. In this report, ENVI-met's modelling output is evaluated for the purpose of evaluating the impact of vegetative filters on particulate matter removal.

2.2. Modelled domain

In most runs, the modelled domain was set to 270 x 180 m with a resolution of 1.5 m horizontally and with 29 vertical layers. Within this domain, the barn buildings were kept constant, but different vegetative filters were introduced. Each model run was calculating the flow field and concentrations for an hour under close-to neutral stratification.

Typical poultry barns in the Lower Fraser Valley are single storey, stud wall structures with clear span truss rafter roof systems. Some broiler barns are two or three storeys high and a few laying barns are two storey buildings with the lower storey being used for manure storage. Wooden pole-frame and rigid-frame structures are also present. Building widths vary depending on their use. For example, a two-row cage laying barn might be as narrow as 5 m, while a broiler barn might be 12 m to 21 m wide. Building lengths are based on the numbers of birds housed and barn equipment

[1] http://www.ENVI-met.com/ (accessed June 2011)

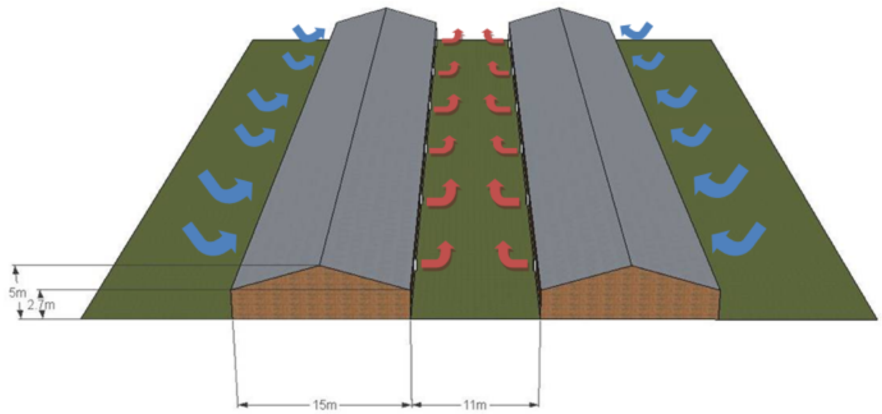


Figure 3 – Diagram of barn orientation to scale with visible venting. Blue are fresh air intakes, red are vents transporting polluted air into the alleyway.

The barn orientation used in this study was a common layout of two parallel, 90 m long, single storey, barns with a peak height of 5 m and a edge height of 3 m and the space between the barns was 12 m. The barns were aligned lengthwise either from West to East or North to South. The wind was set to originate from West at 3 m s^{-1}. The height of the venting was set at a height of 1.5 m. Vents vent polluted indoor air into the spacing between them (red arrows in Figure 3). Six of these vents, for the purposes of this model, were equally spaced along the 90 m long barns at 15 m intervals and 7.5 m from the ends. Also each vent was set to an arbitrary emission strength of 10 mg of PM 10 per second, for a total of 120 mg s^{-1} over the length of the entire length of both barns.

In the analysis wind and concentration of particulate matter were explored in 4 zones of interest all at 1.5 m above ground:

1. *Zone A / Alleyway* – The area 12 m by 90 m directly in between the barns.
2. *Zone B / 0 - 45 m downwind* – The area directly downwind from the barns, starting from the east edge and extending to 45 m past the edge of the barns. The width of this area was 180 m.
3. *Zone C / 45 - 90 m downwind* – Directly downwind from (B) and of identical area and shape (45 m by 180 m)
4. *Zone D / 90 - 130 m downwind* – Downwind from (C) and of identical area and shape as both (B) and (C) (45 m by 180 m)

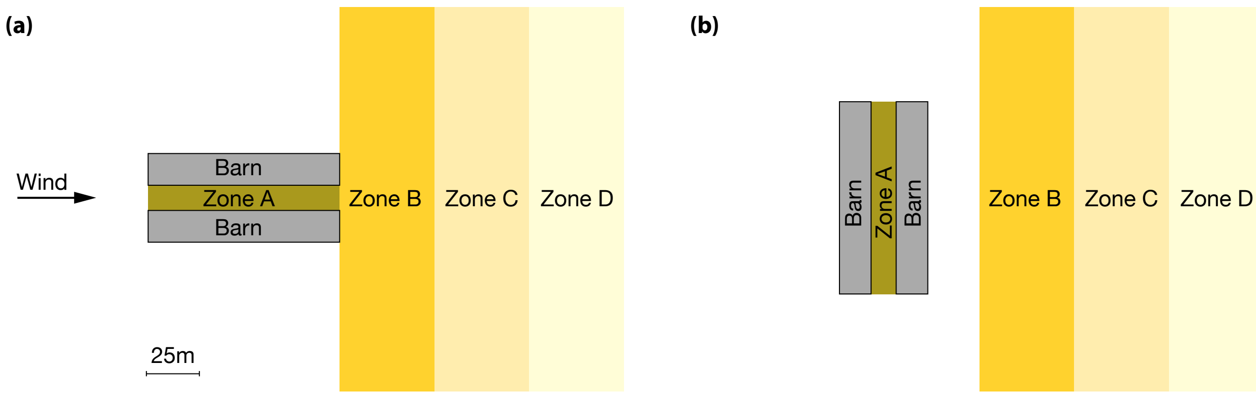


Figure 4 - The four zones analyzed in the study for flow along the barns (a) and flow perpendicular to the barns (b). Wind is from left to right. Zone *A* is the alleyway, zones *B* to *D* are downwind of the approaching flow. All spatial averages were calculated at 1.5 m above ground level.

2.3. Modelling strategy

Firstly, models were run to find the optimal placement location of the vegetative buffer. The main question was whether it was more beneficial to plant a perimeter of trees around the barns (on the property line) or focus on planting the trees in between the barns (in-fill of the `alleyway').

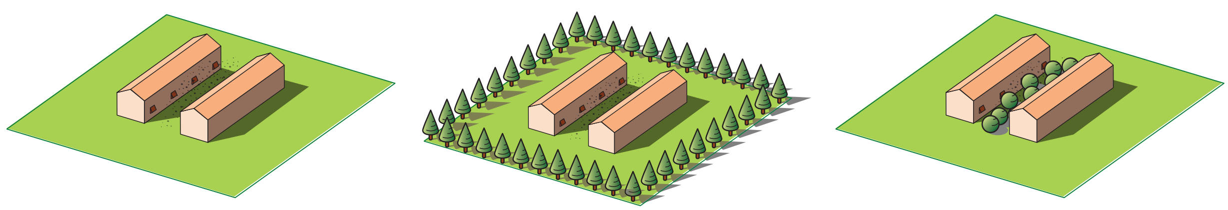
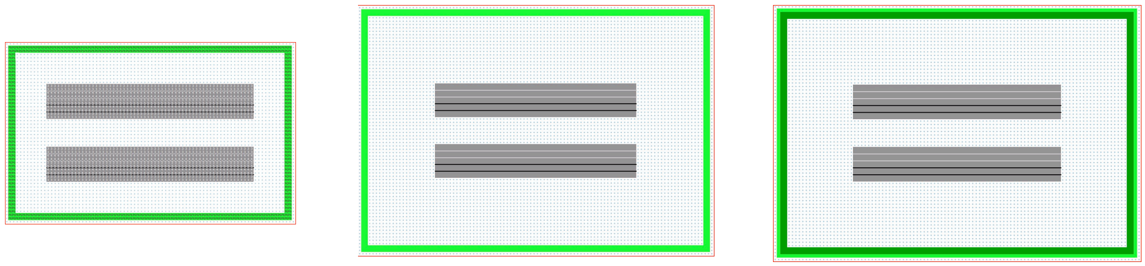


Figure 5 - The basic scenarios modeled in this study: no buffer (R, left), a perimeter cases (P1-3, center) and alleyway infill (I1-3, right).

The specific scenarios modelled were set-up as follows:

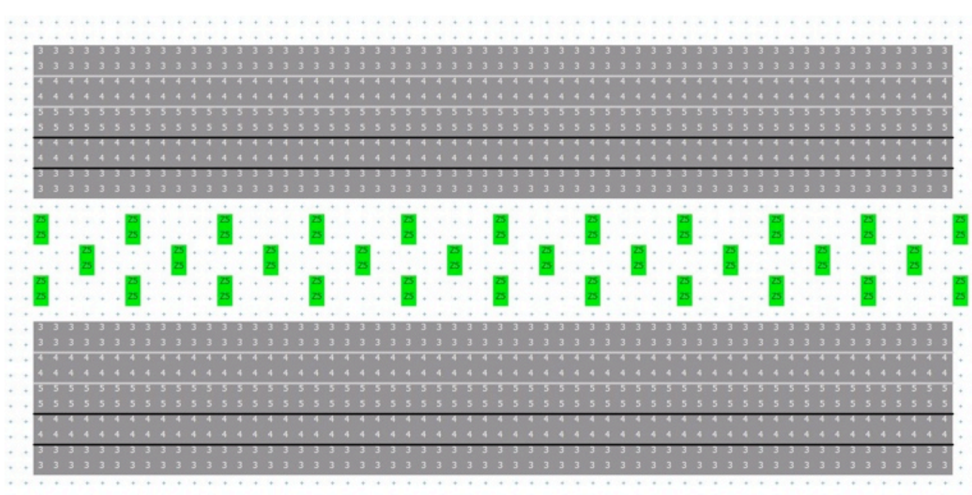
- *Scenario R:* This is the reference case without vegetative buffer.
- *Scenario P1:* A perimeter of dense coniferous trees (hedge) at a distance of 15 m from every edge of the barns. The trees were set a height of 6 m, a leaf area density (LAD) of 1.5 $m^2 m^{-3}$, and the width of the hedge was 3 m wide at all points. The total tree volume is 6,912 m^3.
- *Scenario P2:* A perimeter of dense coniferous trees (hedge) at a distance of 30 m from every edge of the barns. The total tree volume is 7,992 m^3. All other settings same as in Scenario P1.
- *Scenario P3:* This case was using the same dense coniferous hedge at a distance of 30 m with an addition of 15 m tall deciduous trees on the interior of the hedge. These deciduous trees had a distinct crown layer that started at 2 m, and they reached a maximum LAD of 2.18 $m^2 m^{-3}$ at 10.5 m in height. The total tree volume is 23,976 m^3.



P1 P2 P3

Figure 6 - The layout of the vegetative buffer in the perimeter scenarios P1 to P3 relative to the size of the barns (gray). Light green shows coniferous hedges of 6 m height, dark green (in P3) are deciduous trees of 15 m height.

- *Scenario I1:* Dense shrubs in alleyway - This scenario involves a 2 m shrub-like vegetation with a LAD of 1.5 m^2 m^{-3}, and a staggered alignment, with a plan area density (PAD) of 13.3% in the alleyway. The total tree volume is only 288 m^3.
- *Scenario I2:* Sparse shrubs in alleyway - This scenario is similar to I1, except that there is one third less LAD (0.5 m^2 m^{-3}). The total tree volume is the same (288 m^3), as is the arrangement (PAD 13%, staggered, 2 m high).
- *Scenario I3:* Dense trees in alleyway - This scenario involves 6 m shrub-like trees with a LAD of 1.5 m^2 m^{-3}, and a staggered alignment, with a plan area density (PAD) of 13.3% in the alleyway The total tree volume is only 864 m^3.



I1-3

Figure 7 - The alignment of a the shrubs / trees representing a buffer between the barns with a staggered layout and a PAD of 13.3% in Scenario I1, I2 and I3 (each grid point is 1.5m x 1.5m, gray areas are barns).

Informed by the model output of the above scenario, further systematic cases then commenced to explore several variables and their effect on wind reduction of scenario A. There were 3 variables explored to see their effect on wind reduction between the barns:

1. *Height* – The height of the trees in between the barns ranging from 1 m to 15 m. During the testing for height, the leaf area density (LAD, see below) was set to 1.5 m^2 m^{-3}, and the plan area density (PAD, see below) was set to 13.3% in a staggered arrangement (Fig. 7).

2. *Leaf Area Density (LAD)* – This is a measure of the density/porosity of the vegetation in m^2/ m^3 which ranged from 0.25 m^2 m^{-3} to 2.25 m^2 m^{-3}. During the testing for LAD the height was set at 5 m and the PAD was staggered and set to 13.3%.

3. *Plan Area Density (PAD)* – The percentage of the area between the barns that is covered in vegetation. This PAD was separated into 2 arrangements - staggered and aligned. In the model runs for PAD, the LAD was set to 1.5 m^2 m^{-3}, and the height was set to 5 m.

2.4. Model assumptions

Because we ran the models for an hour for each scenario, we assume steady state when extracting the data. This was tested by running a few of the models for 3 hours and comparing the results to those run for only 1 hour.

The values obtained for concentrations are relative values as the sources were set at an arbitrary rate of 10 mg s^{-1} per vent. This was done so the data could be scaled to any scenario that may arise, e.g. for a barn that has venting at 25 mg s^{-1} one would simply multiply the concentrations by 2.5 to obtain relevant data. All aerosols released were generic PM10 particles.

We assume close-to neutral atmospheric conditions between 6 am-7 am on a June morning in the Fraser Valley, with an ambient temperature of 293 K (20ºC). The dynamic stability was z/L = -0.02 (L being the Obukhov length, z is the height above ground, here 1.5 m) over the open terrain upwind of the barns.

The exhaust was not heated, and barns did not expel mass in any given direction (both currently not possible with the model). The sources simply inputted PM10 at a rate of 10mg s^{-1} into the grid space it occupied. This means the models assumes a rapid thermal mixing of the warmer interior air with ambient air. Under low-wind situations this assumption clearly does not hold.

3. RESULTS

3.1. Effect of the buffer layout on wind, PM 10 concentrations and PM 10 deposition

The first set of scenarios tested the effect of planting trees in a perimeter around the barns (Scenarios P1 to P3). These three perimeter cases were compared to three runs thad shrubs or trees within the alleyway (Scenarios I1 to I3) and a reference case without any buffer (Scenario R).

3.1.1. Effects on mean wind

When compared to the reference case (Scenario R), the maximum reduction in average wind speed close to the vents for the perimeter cases was found for P1, the 15 m perimeter scenario, at an average reduction of 0.1 ms^{-1} (6% reduction) at 1.5 m height, and the least effective was P2, the 30 m perimeter of coniferous trees only with a reduction of only 0.02 ms^{-1} (Table 1).

Table 1 - Average wind velocity at 1.5 m above ground in the different scenarios R, P1-3 and I for zones A to D (see Figure 3). Flow is along the barns.

	Average wind velocity *u* ($m\ s^{-1}$)				Relative change to reference			
Scenario	*Zone A*	*Zone B*	*Zone C*	*Zone D*	*Zone A*	*Zone B*	*Zone C*	*Zone D*
Treeless (R)	1.81	1.72	1.78	1.77				
15m Perimeter hedge (P1)	1.71	1.55	1.76	1.77	-6%	-10%	-1%	0%
30m Perimeter hedge (P2)	1.79	1.52	1.66	1.76	-1%	-12%	-7%	-1%
30m Perimeter tall (P3)	1.77	1.64	1.66	1.77	-2%	-5%	-7%	0%
Dense shrubs in alleyway (I1)	1.16	1.71	1.78	1.77	-36%	-1%	0%	0%
Sparse shrubs in alleyway (I2)	1.30	1.71	1.78	1.77	-28%	-1%	0%	0%
Trees in alleyway (I3)	0.94	1.70	1.78	1.77	-48%	-1%	0%	0%

Table 2 - Same as Table 1 for selected runs but for flow perpendicular to the barns.

	Average wind velocity *u* ($m\ s^{-1}$)				Relative change to reference			
Scenario	*Zone A*	*Zone B*	*Zone C*	*Zone D*	*Zone A*	*Zone B*	*Zone C*	*Zone D*
Treeless (R)	0.31	1.80	1.80	1.78				
15m Perimeter hedge (P1)	0.32	1.64	1.78	1.77	3%	-9%	-1%	-1%
30m Perimeter tall (P3)	0.31	1.56	1.76	1.78	0%	-13%	-2%	0%
Dense shrubs in alleyway (I1)	0.29	1.80	1.80	1.78	-6%	0%	0%	0%

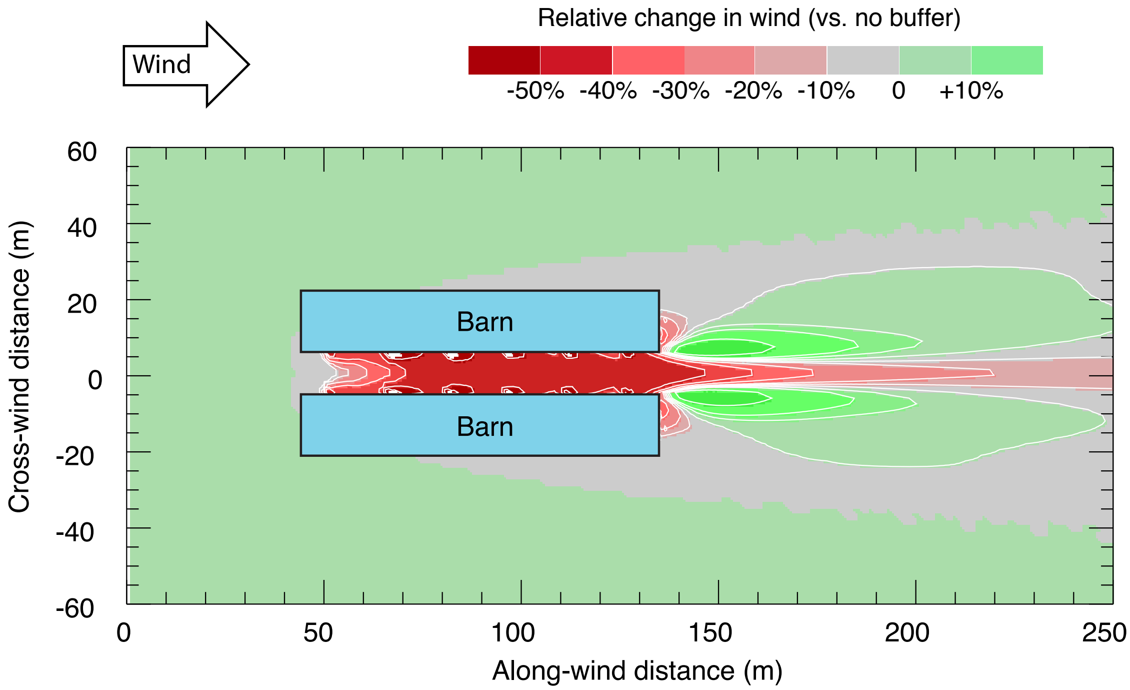


Figure 8 - Change of the mean wind at 1.5 m in Scenario I (alleyway infill) relative to Scenario R (without buffer). Red areas are areas of slowing, green show areas of acceleration relative to Scenario R. The undisturbed wind is from left to right and 1.77 m s^{-1} at 1.5 m height.

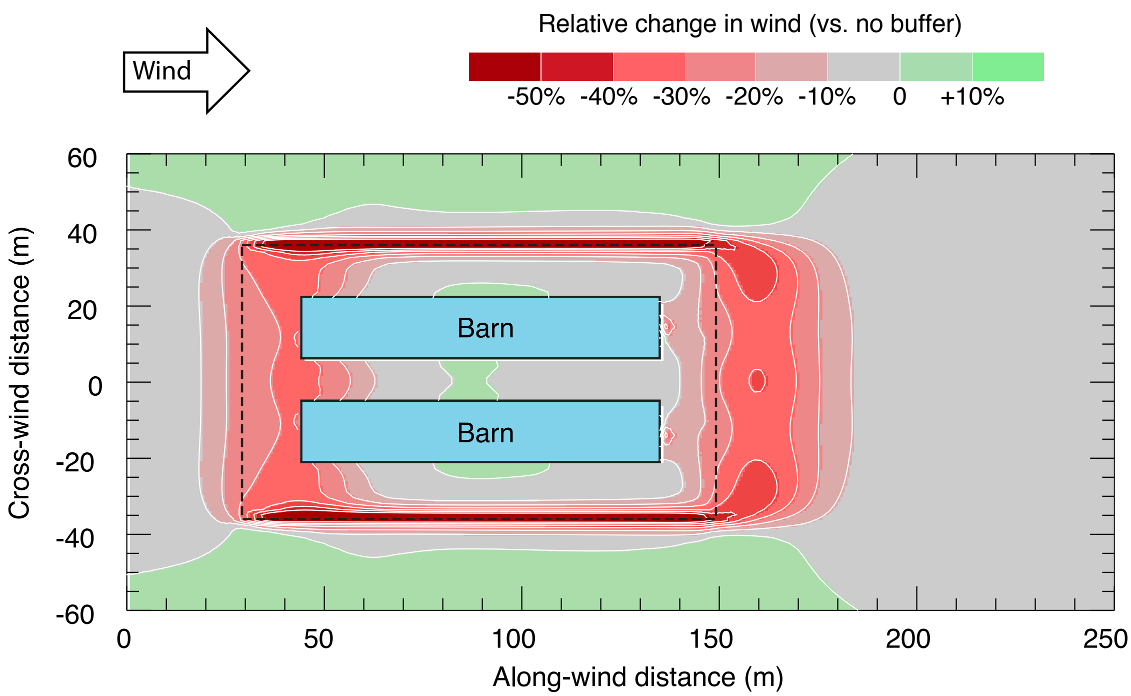


Figure 9 - Same as Figure 8, but for the difference between Scenario P1 (15 m hedge) and Scenario R (without buffer).

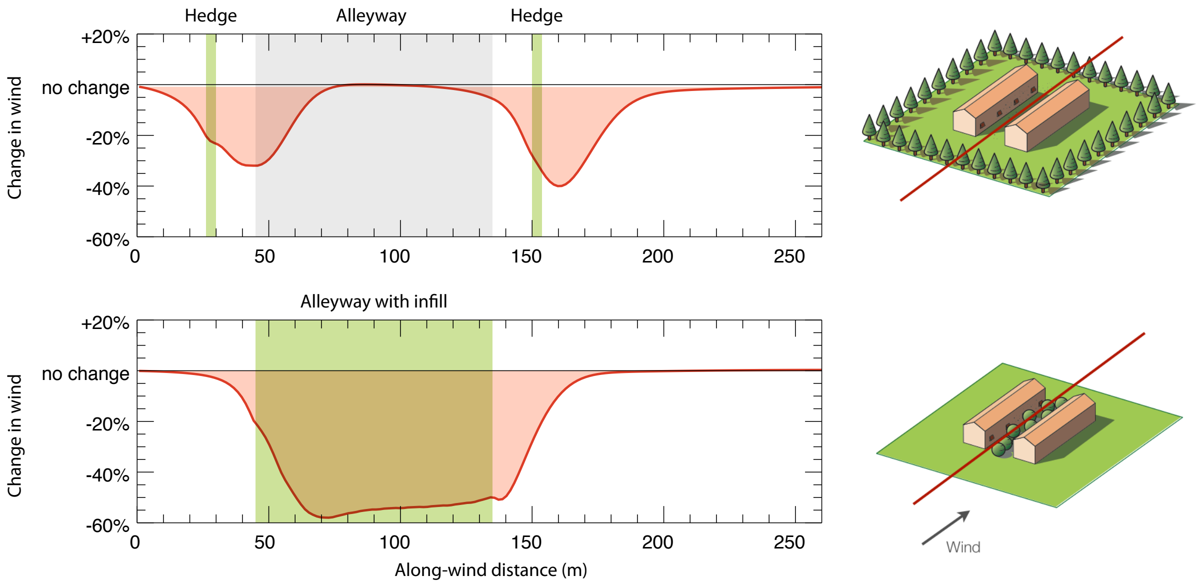


Figure 10 - Reduction in wind speed along a transect through the alleyway at 1.5 m height for scenario P1 (top) and I (bottom). Wind is from left to right (undisturbed upwind is 1.77 m s^{-1} at 1.5 m height)

This compares to a 0.65 ms^{-1} (36%), 0.65 ms^{-1} (28%) and (48%) decrease of the average wind in alleyway in Scenarios *I1, I2* and *I3*. Generally, the changes are less with wind perpendicular to the alleyway (Table 2).

3.1.2. Effects on concentrations

The PM10 concentration close to the vents at 1.5 m was more affected by the scenarios with infill rather than the perimeter cases. Table 3 shows little sensitivity to concentration changes with a perimeter (*P1-P3*), and a much larger change from the different infill cases described above (Scenario *I*). Also effects are more relevant for flow along the barn (Table 3) compared to perpendicular to the barn (Table 4).

It is evident that infilling the alleyway with shrubs is a more effective and efficient way of reducing the mean wind and increasing concentrations at the height of the vents in the alleyway.

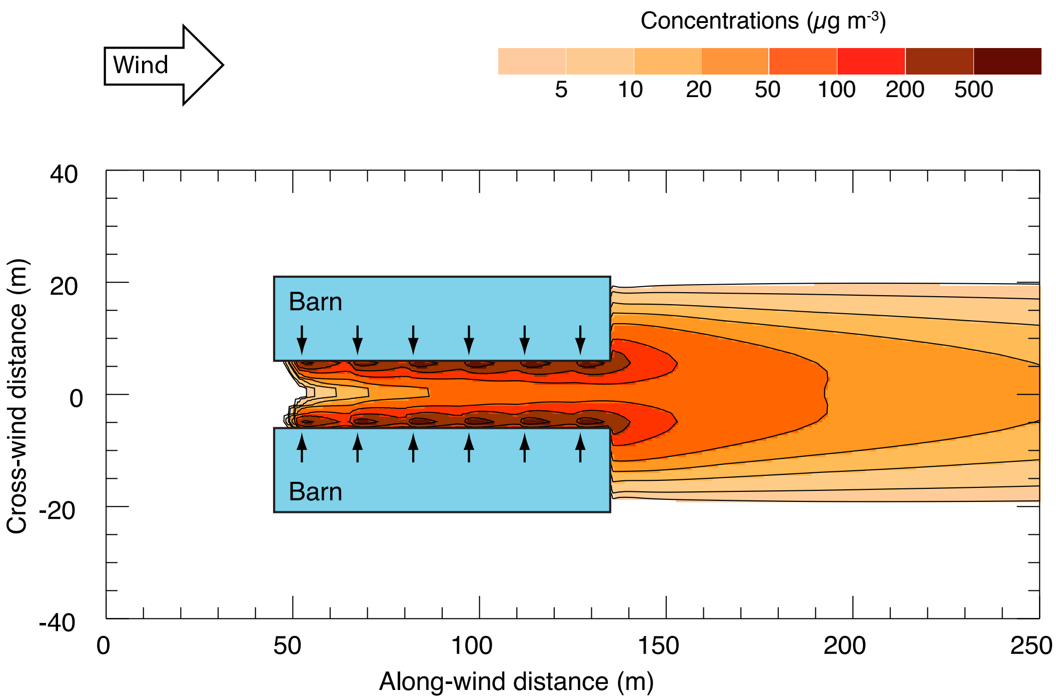


Figure 11 - Concentrations at 1.5 m above ground without any trees (Scenario R). The arrows denote the location of the vents. Wind is at from left to right (undisturbed upwind is 1.77 m s^{-1} at 1.5 m height). The emissions strengths are set to 10 mg s-1 per vent. Background concentration is zero.

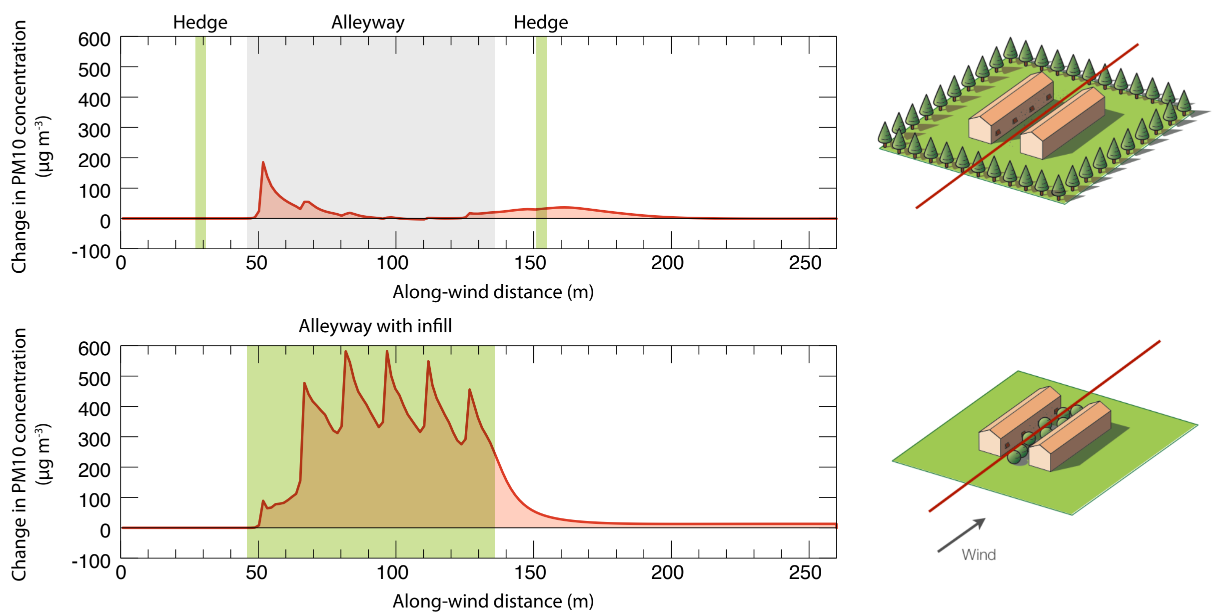


Figure 12 - Increase in PM10 concentration along a transect through the alleyway at 1.5 m height for scenario P1 (top) and I (bottom) at cross-wind location 0m (middle of canyon). Wind is from left to right. Background concentration is zero.

Table 3 - Average PM-10 concentrations at 1.5 m above ground level in the different scenarios for flow along the barns.

	Average concentration ($\mu g\ m^{-3}$)				Relative change to reference			
Scenario	*Zone A*	*Zone B*	*Zone C*	*Zone D*	*Zone A*	*Zone B*	*Zone C*	*Zone D*
Treeless (R)	598	57	31	21				
30m Perimeter hedge (P2)	592	59	33	22	-1%	+4%	+6%	+5%
30m Perimeter tall (P3)	618	63	35	24	+3%	+11%	+13%	+14%
Alleyway infill (I1)	759	61	34	24	+27%	+7%	+10%	+14%
Dense shrubs in alleyway (I1)	824	58	31	22	+38%	+2%	0%	+5%
Sparse shrubs in alleyway (I2)	716	60	32	22	+20%	+5%	+3%	+5%
Trees in alleyway (I3)	825	58	31	22	+38%	+2%	0%	+5%

Table 4 - Same as Table 3 for selected cases but for flow perpendicular to the barns.

	Average concentration ($\mu g\ m^{-3}$)				Relative change to reference			
Scenario	*Zone A*	*Zone B*	*Zone C*	*Zone D*	*Zone A*	*Zone B*	*Zone C*	*Zone D*
Treeless (R)	568	41	28	21				
15m Perimeter hedge (P1)	503	41	28	21	-11%	0%	0%	0%
30m Perimeter hedge (P2)	522	42	30	22	+4%	+2%	+7%	+5%
30m Perimeter tall (P3)	587	46	32	24	+12%	+10%	+7%	+9%
Alleyway infill (I)	627	43	29	22	+7%	-7%	-9%	-8%

3.1.3. Effects on PM10 deposition

The PM10 deposition model included in ENVI-met is only considering gravitational effects and no impactation (Bruse, 2007), so results on PM10 deposition are considered a lower limit. Actual deposition might include impactation and wet deposition on leaves.

Table 5 summarizes the total gravitational deposition on ground, leaves, and the roof of the barns for the six scenarios as provided by the vertically integrated ENVI-met output.

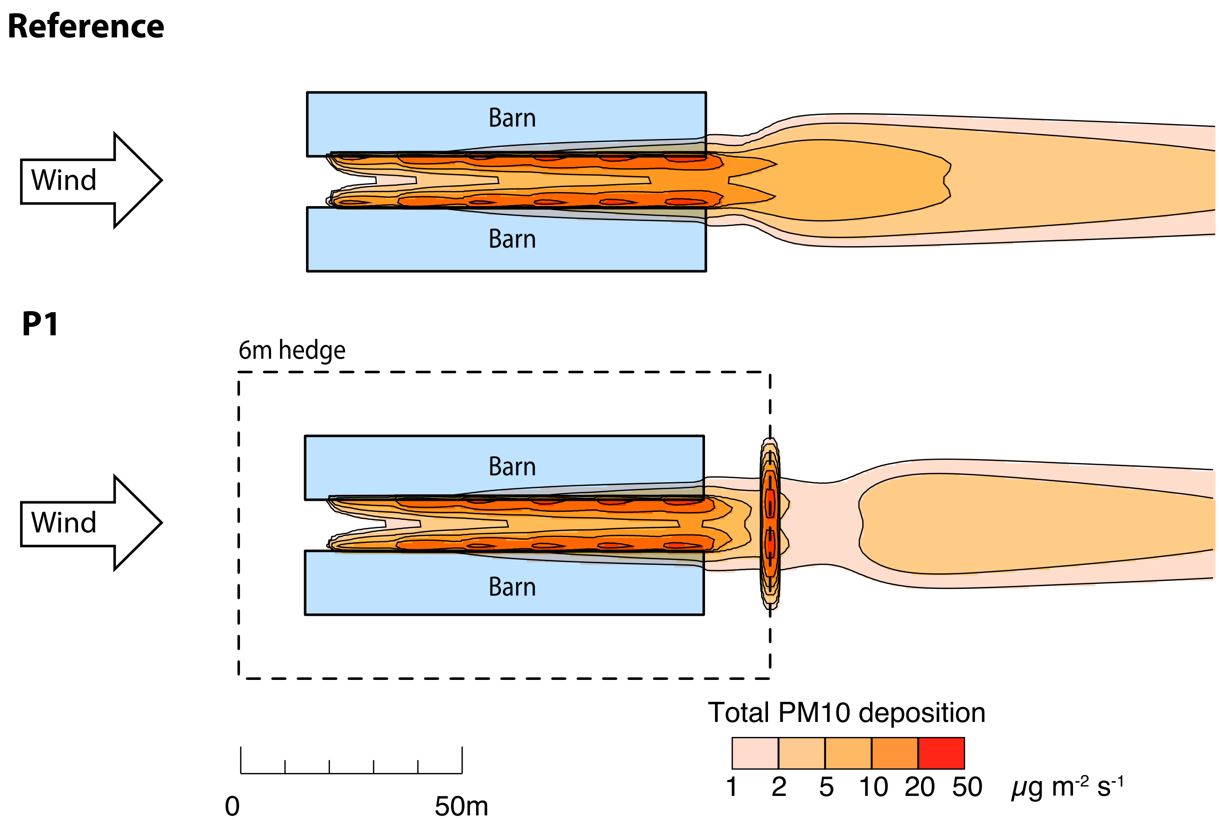


Figure 13 - Total calculated (vertically integrated) gravitational settling of PM10 for a case with no buffer and for scenario P1 with a 6 m hedge. Note the increase of deposition on the hedge, but also the reduced deposition in the lee of the hedge.

Table 4 - Total calculated gravitational settling of PM10 on the ground within the property line (Zones A to D), the vegetative buffer and on roofs of the barns.

	Total grav. deposition ($\mu g\ s^{-1}$)			Fraction of total emissions removed by		
Scenario	*Ground*	*Trees*	*Roofs*	*Ground*	*Trees*	*Roofs*
Treeless (R)	35.7	0.0	0.9	29.7%		0.7%
30m Perimeter hedge (P2)	30.0	3.7	1.2	25%	3.1%	1%
30m Perimeter tall (P3)	31.5	2.6	1.0	26.2%	2.2%	0.8%
Alleyway infill (I1)	33.9	3.4	1.1	28.2%	2.8%	1%
Dense shrubs in alleyway (I1)	17.4	9.5	0.9	14.5%	7.9%	0.7%
Sparse shrubs in alleyway (I2)	28.0	4.3	0.9	23.3%	3.6%	0.7%
Trees in alleyway (I3)	17.2	10.9	0.8	14.3%	9.1%	0.7%

Although both, concentrations were substantially increased and wind was reduced in the infill scenarios, the faction of PM 10 settled on leaves is in all cases less than 10%, and for the perimeter cases even less than 4%. The effect of direct deposition on leaves is minor. Moreover, the vegetation settles on the expense of the settlement on the ground (Table 4), when vegetation was present, the gravitational setting on the ground was less.

This is illustrated in Figures 13 and 14, where the scenarios with vegetation increase settling at the location of the vegetative buffer, but show reduced deposition in the shelter (before and the cavity behind the buffer elements).

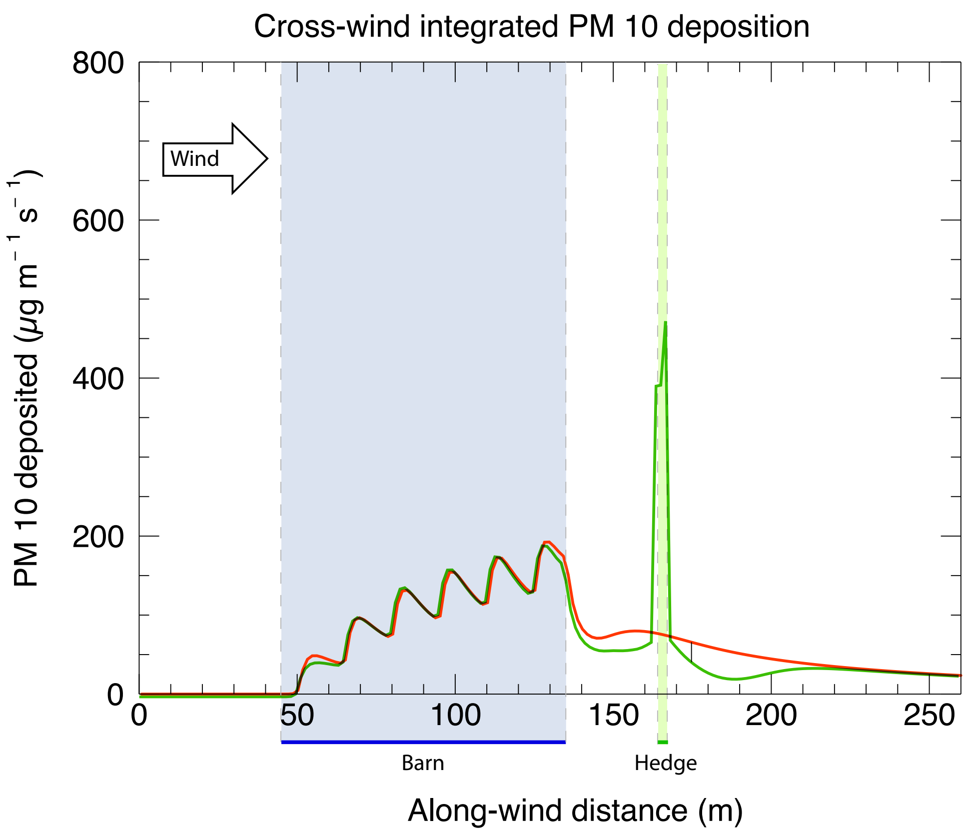


Figure 14 - Total calculated (vertically and cross-wind integrated) gravitational settling of PM10 as a function of the along-wind distance through the model domain without any buffer (Scenario R, red) and with a 12m hedge (Scenario P3). Wind is from left to right, and the settling of PM10 responds to the plumes injected by the 2x six vents (peaks along barn).

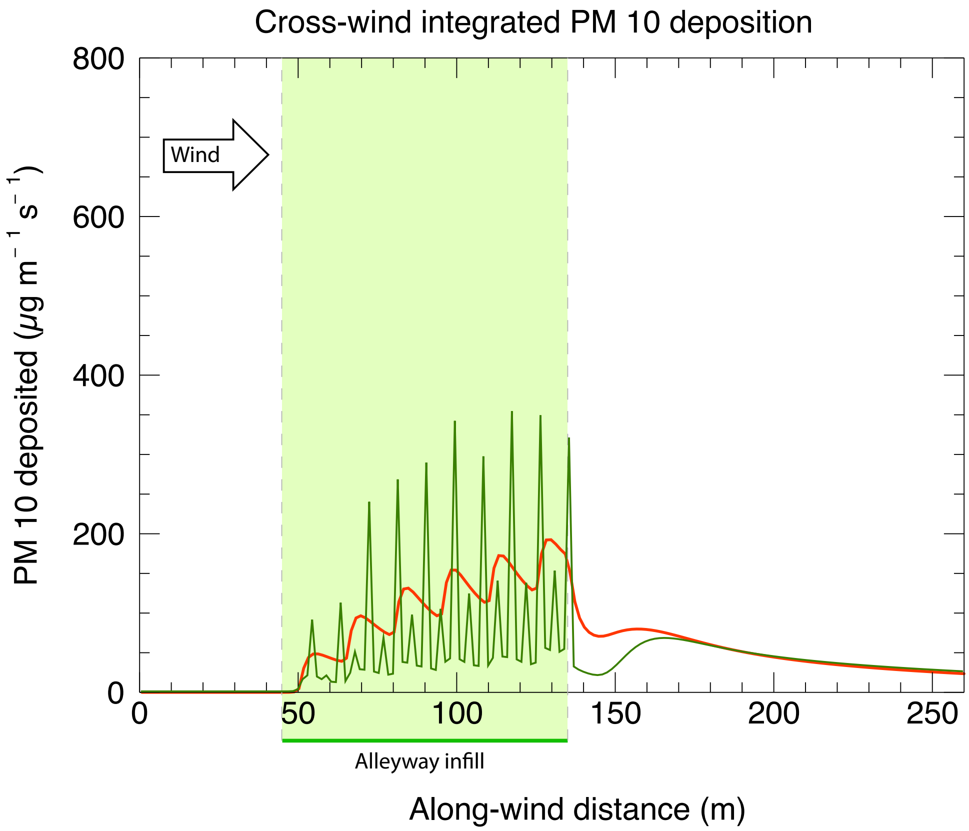


Figure 15 - Same as Figure 13 but comparing the treeless case (Scenario R, red) and with the 2m infill (Scenario I1).

3.2. Systematic cases with a buffer in the alleyway

3.2.1. Sensitivity of wind and PM-10 concentrations to the height of the vegetative buffer

The set-up used in those model runs was a staggered orientation of coniferous hedge-like vegetation with a LAD of 1.5 m^2 m^{-3} with a PAD of 13.3%.

Without any trees between the barns there was an average wind at the height of the vents (1.5 m) of 1.81 m s^{-1}. The maximum reduction occurred when trees planted were 10 - 12m in high which reduced wind at 1.5 m to 0.9 m s^{-1}. After a tree height of 4 m (1.0 m s^{-1}) the effect of wind reduction is not further decreasing (Table 5).

The tree height had a small effect on the wind speed in zone B, and showed no effect in zone C and D (not shown).

The PM10 concentrations in the treeless case were at an average of 598 µgm^{-3} in Zone A (alleyway) at 1.5 m height, and continued to increase as trees of increasing height were added until a peak of 887µgm^{-3} when trees with 12m in height were modelled. Although the maximum concentration is found with 12 m trees, it is important to note that 95% of the effect had been already accounted for by adding trees of an 8 m height, and raising the height after this had little gains (Table 6).

Table 5 - Wind at 1.5 m above ground level as a function of tree height of the infill in zone A (alleyway) and B (downwind). LAD is 1.5 m^2 m^{-3} and PAD is 13.3% (staggered). Flow is along to the barns.

	Average wind (m s^{-1})		Relative change to reference		Std. deviation of wind (m s^{-1})	
Modelled vegetation	*Zone A*	*Zone B*	*Zone A*	*Zone B*	*Zone A*	*Zone B*
No trees (R)	1.81	1.72			0.10	0.21
1 m high infill	1.59	1.72	-12%	0%	0.10	0.21
2 m high infill	1.16	1.71	-36%	-1%	0.19	0.22
4 m high infill	1.00	1.71	-45%	-1%	0.22	0.23
6 m high infill	0.94	1.70	-48%	-1%	0.24	0.23
8 m high infill	0.91	1.70	-50%	-1%	0.25	0.25
10 m high infill	0.90	1.69	-50%	-2%	0.25	0.25
12 m high infill	0.90	1.69	-50%	-2%	0.25	0.25
15 m high infill	0.91	1.70	-50%	-1%	0.25	0.25

Table 6 - PM-10 concentration at 1.5m height as a function of tree height of the infill in zone A (alleyway) and B (downwind). LAD is 1.5 m^2 m^{-3} and PAD is 13.3% (staggered). Flow is along to the barns.

	Average concentration (μg m^{-3})		Relative change to reference		Std. deviation of concentration (μg m^{-3})	
Modelled vegetation	*Zone A*	*Zone B*	*Zone A*	*Zone B*	*Zone A*	*Zone B*
No trees (R)	598	57			481	147
1 m high infill	693	63	+16%	+11%	521	163
2 m high infill	759	61	+27%	+7%	496	160
4 m high infill	792	59	+32%	+4%	499	155
6 m high infill	825	58	+38%	+2%	519	154
8 m high infill	871	59	+46%	+4%	555	158
10 m high infill	882	60	+47%	+5%	564	161
12 m high infill	887	60	+48%	+5%	569	163
15 m high infill	883	60	+48%	+5%	570	164

In zones B, C, and D, changes in concentrations were minor (less than 10% in Zone B) compared to the treeless case. In fact, when comparing the concentrations between the treeless and 15 m height case in zones C and D, there is little to no effect on the PM10 concentrations.

3.2.2. Sensitivity of wind and PM-10 concentrations to leaf area density of the vegetative buffer

Unlike in the model runs with different tree heights, there was no peak in effectiveness for increasing the leaf area density (LAD) on a reduction of mean wind speed within the alleyway. The maximum reduction was found with the highest LAD (2.25 m^2 m^{-3}) with a reduction of 0.99 m s^{-1} (-55%). Changes in LAD had a much smaller effect on the wind speed in Zone B, and no effect in Zones C and D (not shown).

Similar to the effect of LAD on wind speed in the alleyway, there is a steady increase in PM10 concentration from the treeless case until the maximum LAD, at a concentration of 869 μgm^{-3}. As the LAD increased incrementally, the effect of the increase in PM 10 concentrations in the alleyway became less and less. For example, increasing the LAD from 0.25 m^2 m^{-3} to 0.5 m^2 m^{-3} resulted in an increase of 58 μgm^{-3}, yet increasing the LAD from 2.00 m^2 m^{-3} to 2.25 m^2 m^{-3} only saw an increase of 13 μgm^{-3}.

Table 7 - Wind at 1.5 m above ground level as a function of leaf area density (LAD) in zone A (alleyway) and B (downwind) with of a 5 m high infill and a staggered PAD of 13.3%. Flow is along to the barns.

	Average wind ($m\ s^{-1}$)		Relative change to reference		Std. deviation of wind ($m\ s^{-1}$)	
Modelled vegetation	*Zone A*	*Zone B*	*Zone A*	*Zone B*	*Zone A*	*Zone B*
No trees (R)	1.81	1.72			0.10	0.21
LAD 0.25 $m^2\ m^{-3}$	1.50	1.72	-17%	0%	0.11	0.21
LAD 0.50 $m^2\ m^{-3}$	1.30	1.71	-28%	-1%	0.16	0.22
LAD 0.75 $m^2\ m^{-3}$	1.16	1.71	-36%	-1%	0.19	0.22
LAD 1.00 $m^2\ m^{-3}$	1.07	1.71	-41%	-1%	0.21	0.23
LAD 1.25 $m^2\ m^{-3}$	1.00	1.70	-45%	-1%	0.23	0.23
LAD 1.50 $m^2\ m^{-3}$	0.94	1.70	-48%	-1%	0.24	0.24
LAD 1.75 $m^2\ m^{-3}$	0.89	1.70	-51%	-1%	0.24	0.24
LAD 2.00 $m^2\ m^{-3}$	0.86	1.70	-52%	-1%	0.25	0.24
LAD 2.25 $m^2\ m^{-3}$	0.82	1.70	-55%	-1%	0.26	0.24

Table 8 - PM-10 concentration at 1.5 m above ground level as a function of leaf area density (LAD) in zone A (alleyway) and B (downwind) with of a 5 m high infill and a staggered PAD of 13.3%. Flow is along to the barns.

	Average concentration ($\mu g\ m^{-3}$)		Relative change to reference		Std. deviation of concentration ($\mu g\ m^{-3}$)	
Modelled vegetation	*Zone A*	*Zone B*	*Zone A*	*Zone B*	*Zone A*	*Zone B*
No trees (R)	598	57			481	147
LAD 0.25 $m^2\ m^{-3}$	658	58	+10%	+2%	485	152
LAD 0.50 $m^2\ m^{-3}$	716	60	+20%	+5%	501	155
LAD 0.75 $m^2\ m^{-3}$	754	59	+26%	+4%	509	156
LAD 1.00 $m^2\ m^{-3}$	782	59	+31%	+4%	513	155
LAD 1.25 $m^2\ m^{-3}$	805	59	+35%	+4%	516	154
LAD 1.50 $m^2\ m^{-3}$	824	58	+38%	+2%	518	153
LAD 1.75 $m^2\ m^{-3}$	841	58	+41%	+2%	521	153
LAD 2.00 $m^2\ m^{-3}$	856	58	+43%	+2%	523	152
LAD 2.25 $m^2\ m^{-3}$	869	58	+45%	+2%	525	152

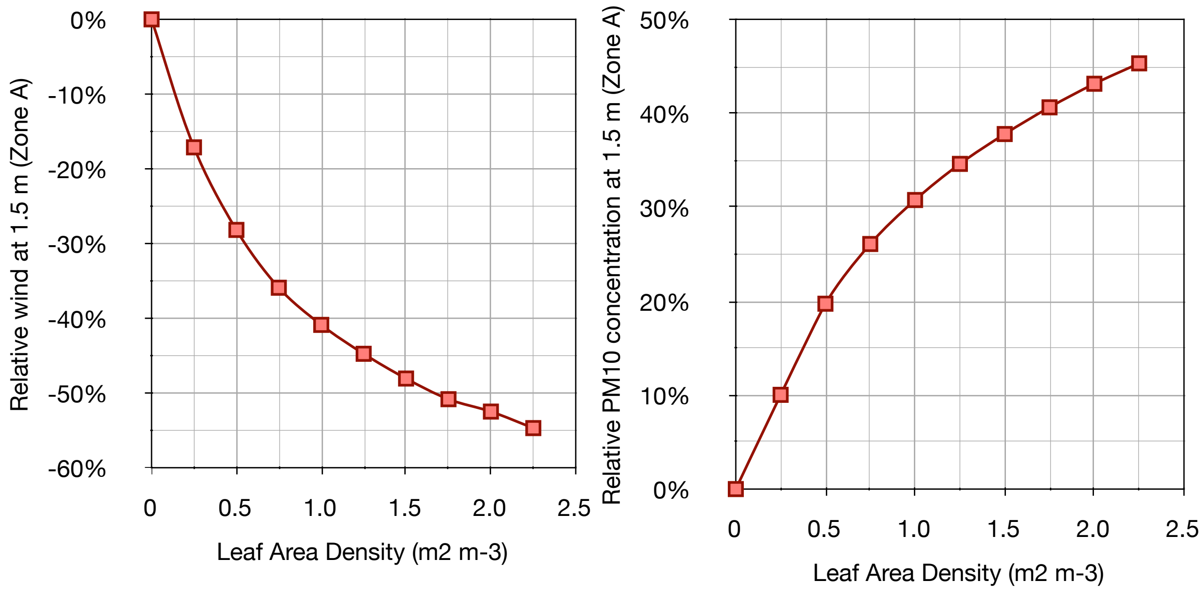


Figure 16 - Spatially averaged mean wind (left) and PM-10 concentration (right) at 1.5 m above ground level in Zone A as a function of leaf area density (LAD) of a 5 m high infill with a PAD of 13.3%.

For zones B, C, and D, there was very little effect of LAD on PM10 concentrations, and the furthest zone (D) saw the least effect. As in the height cases, the maximum LAD in each case saw similar PM10 concentrations in all zones downwind from the barn as the treeless case.

3.2.3. Sensitivity of wind and PM-10 concentrations to plan area density of the vegetative buffer

There were two geometries explored when testing sensitivity to PAD:

- Staggered – orientation of vegetation within the alleyway that is not aligned directly in a row.
- Aligned - orientation of vegetation within the alleyway that is aligned directly in a row.

The set up used in the PAD sensitivity cases was a coniferous, hedge-like vegetation with a LAD of 1.5 m^2m^{-3} and a height of 6 m (Figure 9).

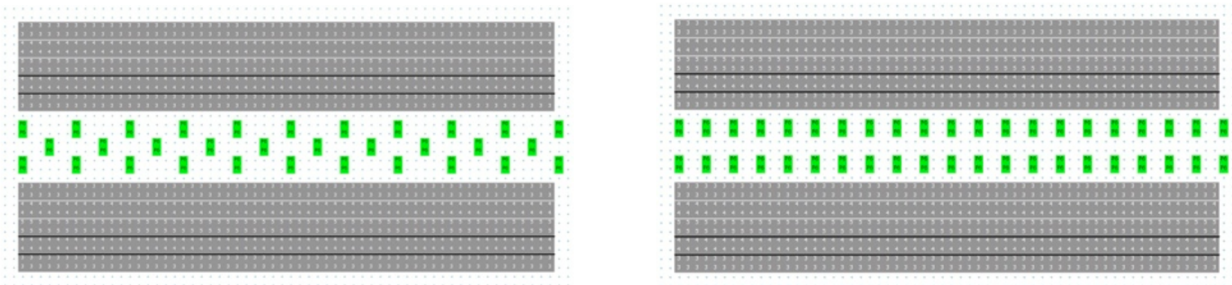


Figure 13 - An example of an aligned orientation (17.5% PAD, left) and a staggered orientation (13.3% PAD, right).

The average wind speed in the alleyway decreased faster as PAD increased with the staggered orientation cases vs. the aligned cases. The reduction of wind speed within the alleyway reached within 2% of the maximum reduction with a PAD of 50% in the staggered case, and little effect was observed by increasing the PAD beyond 50%. With the aligned cases, the reduction of average wind speed within the alleyway increased more steadily until its maximum at 100% PAD. It is important to note that the cases for both 0% and 100% PAD were identical in both the staggered and aligned orientations, but the remainder of the cases were distinct (Table 9).

Both the staggered and aligned PAD orientations had very little effect on the wind speed in zone B, and no effect in zones C and D.

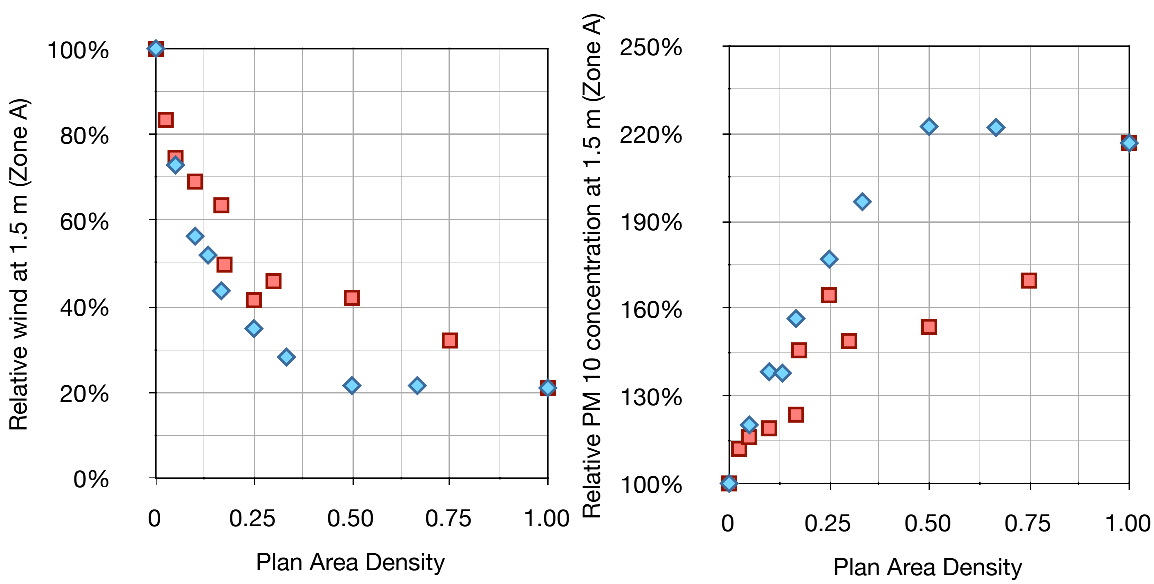


Figure 17 - Spatially averaged mean wind (left) and PM-10 concentration (right) at 1.5 m above ground level in Zone A as a function of plan area density (PAD) of a 5 m high infill with a LAD of 1.5 m^2 m^{-3}. The blue symbols refer to the staggered geometry, the red squares are the aligned geometry.

Table 9 - Wind at 1.5 m above ground level as a function of plan area density (PAD) in zone A (alleyway) and B (downwind) with of a 5 m high infill with a LAD of 1.5 $m^2\ m^{-3}$. Flow is along to the barns.

	Average wind ($m\ s^{-1}$)		Relative change to reference		Std. deviation of wind ($m\ s^{-1}$)	
Modelled vegetation	*Zone A*	*Zone B*	*Zone A*	*Zone B*	*Zone A*	*Zone B*
No trees, PAD 0% (R)	1.81	1.72			0.10	0.21
Aligned						
PAD 2.5%	1.51	1.71	-17%	-1%	0.15	0.21
PAD 5%	1.35	1.71	-25%	-1%	0.21	0.22
PAD 10%	1.25	1.71	-31%	-1%	0.25	0.22
PAD 16.7%	1.15	1.71	-36%	-1%	0.31	0.22
PAD 17.5%	0.90	1.70	-50%	-1%	0.26	0.24
PAD 25%	0.75	1.70	-59%	-1%	0.26	0.24
PAD 30%	0.83	1.70	-54%	-1%	0.27	0.23
PAD 50%	0.76	1.70	-58%	-1%	0.28	0.24
PAD 75%	0.58	1.70	-68%	-1%	0.30	0.25
PAD 100%	0.38	1.69	-79%	-2%	0.17	0.27
Staggered						
PAD 5%	1.32	1.71	-27%	-1%	0.22	0.02
PAD 10%	1.02	1.70	-44%	-1%	0.23	0.02
PAD 13.3%	0.94	1.70	-48%	-1%	0.24	0.02
PAD 16.7%	0.79	1.71	-56%	-1%	0.23	0.02
PAD 25%	0.63	1.70	-65%	-1%	0.24	0.02
PAD 33.3%	0.51	1.70	-72%	-1%	0.25	0.02
PAD 50%	0.39	1.69	-78%	-2%	0.26	0.02
PAD 66.7%	0.39	1.69	-78%	-2%	0.27	0.02
PAD 100%	0.38	1.69	-79%	-2%	0.27	0.02

The average PM10 concentration in the alleyway increased faster as PAD increased with the staggered orientation cases vs the aligned cases. The increase in PM10 concentration within the alleyway saturated with a PAD of 50% in the staggered case, and a small decrease was observed by increasing the PAD to 100%. With the aligned cases, the increase in PM10 concentration within the alleyway increased more steadily until its maximum at 100% PAD (Table 10). It is important to note that the cases for both 0% and 100% PAD were identical in both the staggered and non-staggered orientations, but the remainder of the cases were distinct.

Table 10 - PM-10 concentration at 1.5 m above ground level as a function of plan area density (PAD) in zone A (alleyway) and B (downwind) with of a 5 m high infill with a LAD of 1.5 m^2 m^{-3}. Flow is along to the barns.

	Average concentration (µg m^{-3})		Relative change to reference		Std. deviation of concentration (µg m^{-3})	
Modelled vegetation	*Zone A*	*Zone B*	*Zone A*	*Zone B*	*Zone A*	*Zone B*
No trees, PAD 0% (R)	598	57			481	147
Non-staggered						
PAD 2.5%	669	60	+12%	+5%	498	157
PAD 5%	693	59	+16%	+4%	499	154
PAD 10%	711	59	+19%	+4%	505	153
PAD 16.7%	739	59	+24%	+4%	523	153
PAD 17.5%	871	58	+46%	+2%	568	151
PAD 25%	984	57	+65%	0%	694	148
PAD 30%	890	58	+49%	+2%	589	153
PAD 50%	919	58	+54%	+2%	639	154
PAD 75%	1,014	56	+70%	-2%	678	151
PAD 100%	1,296	47	+117%	-18%	1,007	128
Staggered						
PAD 5%	718	60	+20%	+5%	508	156
PAD 10%	827	58	+38%	+2%	527	152
PAD 13.3%	824	58	+38%	+2%	518	153
PAD 16.7%	936	56	+57%	-2%	575	146
PAD 25%	1,058	55	+77%	-4%	656	144
PAD 33.3%	1,176	54	+97%	-5%	743	142
PAD 50%	1,330	51	+122%	-11%	899	135
PAD 66.7%	1,328	50	+122%	-12%	959	134
PAD 100%	1,296	47	+117%	-18%	1,007	128

In zones B, C, and D, there were gradual decreases in PM10 concentration with increasing PAD in the alleyway. This decrease was greatest within zone B, and least within zone D. Mainly in zone B, a slight noticeable different between staggered and non-staggered orientations were observed, with the staggered orientation decreasing PM10 concentration in zone B faster than with the non-staggered one. In zones C and D, the differences between staggered and non-staggered were negligible.

4. DISCUSSION AND CONCLUSIONS

Buffers increase the surface area (i.e. leaf area) where aerosols can be impacted (filter), and they slow down wind speed and might increase concentrations, so it was postulated that gravitational settling will be more effective (buffer). In this modelling study we only focus on the buffer-function of vegetation.

As expected, vegetative buffers decrease wind and consequently increase concentrations if placed near the vents. Both of those effects are desired in this case. If wind is reduced, concentrations will increase which makes the deposition on leaves more effective, given same source strength. This is because the residence time of an air parcel at a given location inside the filter is longer. However the model results suggest that the effects of turbulence and deflection of the flow are also important and can outweigh those benefits.

4.1. Recommendations to reduce wind near vents

Reducing wind near the vents will not directly reduce emissions, but can be a strategy to enhance the effectiveness of a buffer by increasing concentrations, enhance contact time with the filter, and hence promote gravitational settling (dry and possibly wet). On the other hand, if impaction (not modelled) would more relevant than gravitational settling, the effectiveness of the filter would be reduced with less wind (less flow through filter per time, less number of impact events per time and area). The second point is unlikely, but has not been considered in the model at all.

If reducing wind where concentrations are highest (i.e. near the vents) is a management goal to increase the effectiveness of buffers, the following recommendations will achieve this:

1. A perimeter approach with tall trees is not as effective at reducing the wind speed close to vents as is infilling the canyon with relatively small shrubs. Given that the volume of trees planted is only 300m^3 in a typical infill vs 25,000 m^3 in the largest perimeter case (P3), the cost of the perimeter planting and maintenance would be over 80 times that of the infill case (given a certain cost per tree volume).

2. Within the alleyway the effect of vegetation height levels off at 4 m high trees. This could mean that the best return is with a tree /shrub height of 2-4 m. Planting trees taller than 4m would not add much benefit.

3. Within the alleyway the effect of increasing leaf area density does not peak. Wind speed continues to be reduced as LAD is increased, with the maximum average decrease of wind within the alleyway of 55%. Recommendation is medium to high density with evergreen structure to reduce wind (this does not mean that the filter should be dense).

4. Within the alleyway, staggered orientations of vegetation have a substantially greater effect in reducing wind than aligned configurations at the same plan area density (PAD). For example, at

16.7% PAD, a staggered orientation reduced the wind by 56% vs. only 36% reduction observed using an aligned orientation.

4.2. Recommendations to increase concentrations near buffer

Increasing the concentrations near the buffer is achieved by managing the wind and designing layouts that discourage dispersion and mixing. If increasing concentrations near the buffer is a management goal, the following recommendations will achieve this:

1. Again, the perimeter approach with tall trees is not as effective at increasing concentrations close to the buffer as is infilling the canyon with relatively small shrubs. The perimeter vegetation is too far from the sources to affect concentrations substantially. At this distance, most of the PM10 plume will move across the barrier.
2. Similar to wind, within the alleyway the effect of vegetation height levels off at 4 m high trees. Planting trees taller than 4m would not add much benefit on increasing concentrations.
3. Within the alleyway the effect of increasing leaf area density does not peak. Concentrations are highest with a completely closed tree canopy (although this is an unrealistic scenario from a logistical perspective).
4. Within the alleyway, staggered orientations of vegetation have a substantially greater effect in enhancing concentrations near the buffer than aligned configurations at the same plan area density (PAD).

4.3. Recommendations to promote gravitational settling

Even in the best case, only about ~10% of the emitted PM10 was deposited on the buffer vegetation in the model runs. In none of the scenarios, total PM10 leaving the property was significantly reduced. In some cases the enhanced deposition on leaves was offset by much reduced deposition on ground behind buffer elements. This is explained by the enhanced turbulence created by the vegetation which mixes the PM10 better with the faster flow above the buffer and inhibits deposition.

Unfortunately, the current ENVI-met version is not treating all aspects of PM10 deposition and further studies will need to quantify in more detail the effects of impaction and wet deposition effects.

4.4. Overall evaluation of the modelling approach

The ENVI-met model has been demonstrated a practical tool that allows rapid modelling of simple and more complex geometries of buffers and barns and their effect on wind and concentrations of PM10. Although the model has been designed for urban air quality management, the scale of the model is easily transferrable to agricultural facilities. The lack of a detailed particulate matter deposition module however is a restricting factor at this point. A new version of ENVI-met (4.0) planned for release in 2012 might add additional functionalities in this direction and is worth further testing.

References

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