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Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter

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HIGHLIGHTS

- Vegetation barriers altered near-road black carbon concentrations.
- Vegetation reduced downwind black carbon concentrations by approximately 12%.
- Downwind fine and coarse particle concentration were unaffected by vegetation.
- Black carbon gradients more gradual behind vegetation compared to a clearing.

ARTICLE INFO

ABSTRACT

One proposed method for reducing exposure to mobile source air pollution is the construction or preservation of vegetation barriers between major roads and nearby populations. This study combined stationary and mobile monitoring approaches to determine the effects of an existing, mixed-species tree stand on near-road black carbon (BC) and particulate matter concentrations. Results indicated that wind direction and time of day significantly affected pollutant concentrations behind the tree stand. Continuous sampling revealed reductions in BC behind the barrier, relative to a clearing, during downwind (12.4% lower) and parallel (7.8% lower) wind conditions, with maximum reductions of 22% during the late afternoon when winds were from the road. Particle counts in the fine and coarse particle size range (0.5–10 μm aerodynamic diameter) did not show change. Mobile sampling revealed BC concentration attenuation, a result of the natural dilution and mixing that occur with transport from the road, was more gradual behind the vegetation barrier than in unobstructed areas. These findings suggest that a mature tree stand can modestly improve traffic-related air pollution in areas located adjacent to the road; however, the configuration of the tree stand can influence the likelihood and extent of pollutant reductions.

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1. Introduction

Public health concerns related to near-road air quality have become a pressing issue due to the increasing number of epidemiological studies suggesting that populations spending significant amounts of time near heavily trafficked roads are at a greater risk of adverse health effects (HEI, 2010). These effects may be attributed to increased exposure to particulate matter, gaseous criteria pollutants, and air toxics emitted by vehicular traffic. The significant impact of traffic emissions on urban populations all over the world has motivated research on methods to reduce exposure to these pollutants. While emission control techniques and programs to directly reduce emitted air pollutants are vital

components of air quality management, other options, including the preservation and planting of vegetation and the construction of roadside structures such as noise barriers, may be near-term mitigation strategies useful for urban developers. These methods, if successful, can complement existing pollution control programs or provide measures to reduce impacts from sources that are difficult to mitigate.

Despite recent studies employing modeling, wind tunnel, and field measurements to evaluate the role of vegetation on pollutant concentrations in urban areas (Baldauf et al., 2008; Brode et al., 2008; Hagler et al., 2012; Nowak, 2005; Nowak et al., 2000; Stone and Norman, 2006), the extent to which vegetation barriers can reduce air pollution near roads under varying traffic and meteorological conditions remains uncertain.

Vegetation, particularly trees, can reduce a population's exposure to air pollution through the interception of airborne particles (Petroff et al., 2009) or through the uptake of gaseous air pollution via leaf stomata on the plant surface (Smith, 1990). Noise barriers combined with mature

vegetation have been found to result in lower ultrafine particle concentrations along a highway transect compared to an open field or a noise barrier alone (Baldauf et al., 2008; Bowker et al., 2007). Pollution removal (O_3, PM_{10}, NO_2, SO_2, and CO) by urban trees in the United States (US) has been estimated at 711,000 t per year, or about 11 g per square meter of canopy cover based on hourly meteorological and pollution concentration data from across the continental US (Nowak et al., 2006). Removal of gaseous pollutants by trees can be permanent, while trees typically serve as a temporary retention site for particles. The removed particles can be resuspended to the atmosphere during turbulent winds, washed off by precipitation, or dropped to the ground with leaf and twig fall (Nowak et al., 2000). This temporary removal increases the uncertainty concerning the overall effect of trees on particulate air pollution.

Trees can also act as barriers between sources and populations, although vegetation is inherently more complex to study than solid structures and the effectiveness of vegetative barriers at reducing ultrafine particle (UFP) concentration has been shown to be variable (Hagler et al., 2012). This variability is likely due to a number of confounding factors. The complex and porous structure of trees and bushes can modify near-road concentrations via pollutant capture or through altering air flow, which can result in either diminished dispersion through the reduction of wind speed and boundary layer heights (Nowak et al., 2000; Wania et al., 2012) or in enhanced dispersion due to increased air turbulence and mixing. Recirculation zones have also been observed immediately downwind of forested areas with a flow structure consistent with an intermittent recirculation pattern (Detto et al., 2008; Frank and Ruck, 2008). Vegetation type, height, and thickness can all influence the extent of mixing and pollutant deposition experienced at the site. The built environment also matters greatly — air flow and impacts of trees are substantially different for a street canyon environment than an open highway environment (Buccolieri et al., 2009, 2011; Gromke et al., 2008). Uncertainty remains concerning the degree to which vegetation reduces (or increases) pollutant concentrations in the near-road environment under varying meteorological conditions and vegetation characteristics. By characterizing the effects of a tree stand on near-road air quality in an open highway environment over a range of meteorological and traffic conditions, this study provides insight into site characteristics that are relevant to near-road neighborhoods along major highways and could be advocated and implemented as a mitigation strategy.

2. Methods

2.1. Site description and sampling schedule

This field study occurred in Detroit, Michigan on a golf course adjacent to Interstate 275 (I-275) — a six-lane highway running generally north-south with an annual average daily traffic (AADT) of approximately 120,000 vehicles. The site was selected based on these roadside area properties: an area of vegetation barrier adjacent to an area without any obstructions to air flow along the same stretch of limited-access highway. Additional site requirements included high roadway traffic volume and the avoidance of other known confounding emission sources. Both the clearing and the tree stand were separated from the highway by a bike lane. The tree stand ranged from approximately 5–78 m in width at the locations where sampling occurred, and consisted primarily of maple and oak trees extending to 10 m in height with underbrush creating a barrier from ground-level to the top of the tree canopy.

Sampling was conducted using two portable samplers (PSs) during May and June, 2011, for a total of 28 days. One sampler (PS-C) was located at a fixed site in the clearing, approximately 30 m from the highway, without any obstructions to air flow between the highway and the sampler or within 15 m in all other directions. The site was approximately 40 m from the beginning of the vegetative barrier section. Wind speed and direction were also measured continuously at this

site. A second sampler (PS-T) was located at a fixed site approximately 340 m north, at an equal distance from the highway and behind an approximately 15 m thick tree stand with a measured leaf area index (LAI) of 3.9. While the PS-C site experienced no interruption in sampling aside from brief periods of maintenance, on 13 of the sampling days the PS-T stationary data time series had approximately 2 h per day where the sampler was re-located every 10 min to sample sequentially along a series of sampling points located both behind the tree stand and in the clearing (Fig. 1). The stationary and mobile data were isolated in separate analyses.

2.2. Analytical instruments and methods

Table 1 lists the measurements collected during this field study, including measurement parameters, sampling frequency, and instruments used. Air pollutants measured on board PS-C and PS-T included black carbon (BC) using a microaethalometer (AE-51, Magee Scientific, Berkeley, California, USA) and particle number (PN) concentration in the fine to coarse size range using a hand-held particle counter (HHPC-6, MetOne, Grants Pass, Oregon, USA). During stationary sampling, the instruments were located inside weatherproof boxes with a common shared stainless steel inlet, sampling at 1.5 m above the ground. Inside the weatherproof box, flexible antistatic tubing connected the instruments to the external inlet. The tubing was kept short (0.6 m) and aligned to provide minimal bends to the instrument sampling larger particles (HHPC-6), minimizing particle loss. Each box configuration contained the same setup, including materials, sampler locations, and tubing lengths. The HHPC-6 measures particle number concentration in six size bins (0.5–0.7, 0.7–1.0, 1.0–2.0, 2.0–5.0, 5.0–10.0, >10.0 μm). Although the HHPC-6 is designed primarily for indoor applications and undercounting is a concern due to particle coincidence, a previous study found that the HHPC-6 correlated well with a $PM_{2.5}$ federal equivalence method under urban ambient conditions (Papier, 2008). Daily zero checks used a high efficiency particulate air (HEPA) filter placed over the sampling inlet. Data logging occurred internally after daily time-synchronization of all instruments to within 10 s.

Wind direction and speed measurements were conducted using an ultrasonic anemometer located in the clearing within 3 m of PS-C. Leaf area index (LAI), a metric of estimated leaf area per unit ground area, was measured at eight different sites along the edge of the tree stand with a plant canopy analyzer (LAI2000, LI-COR Biosciences, Lincoln, Nebraska, USA), a hand-held meter that assesses solar radiation transmission through overlapping foliage. Hourly traffic counts were obtained from the Michigan Department of Transportation, which maintains a permanent traffic counting station just north of the study site along the same stretch of limited-access highway.

2.3. Collocated sampling

Over the course of the study, PS-T and PS-C were moved to the same location for 10–20 min on 13 of the sampling days and for 3, 23, and 27 h on three of the sampling days to conduct side-by-side sampling to determine potential bias between the samplers. The collocated measurements of black carbon (BC) concentration and particle number (PN) concentration by bin were assessed at 1, 2, 3, 5, and 10 minute averaging intervals through visual inspection and least-squares regression. A fixed time base version of the aethalometer optimized noise-reduction algorithm (ONA) (Hagler et al., 2011) was applied to the BC data set. Any data that showed insufficient change in the light attenuation signal over the target averaging period (i.e., low signal-to-noise ratio) were removed from analysis. After assessing various time intervals, three-minute averaging was chosen for the analysis to maximize sample number while minimizing noise. Three-minute averaging of the collocated data resulted in $R^2 \geq 0.97$ for each of the lower five PN bin sizes (0.5–10.0 μm) and $R^2 = 0.80$ for BC. Fig. 2 shows the collocated measurements and least-squares regression results. Some bias was observed between the two HHPC instruments: comparing PS-T with PS-C HHPC-6

Fig. 1. Map of the study area in Detroit, Michigan showing the air monitoring locations. The star symbols indicate the locations of the fixed sites in a clearing (PS-C) and behind a tree stand (PS-T). The large yellow circles represent the intended sequential sampling stops, while the smaller, blue dots show the actual sampling locations during the mobile sampling campaigns. Changes in sampling locations from the intended sites were often a result of water hazards due to weather or use of the golf course.

units, bin 3 (1.0–2.0 μm) and bin 5 (5.0–10.0 μm) were 23% higher and 20% lower, respectively. Other size ranges, bins 1 (0.5–0.7 μm), 2 (0.7–1.0 μm), and 4 (2.0–5.0 μm), did not display a bias. The measurements of BC by PS-T were 13% higher than PS-C. The observed biases were consistent across averaging times. While filter loading bias may impact the BC data (Kirchstetter and Novakov, 2007), both instruments had internal filters changed simultaneously each day. To correct for the bias between instruments, measurements from PS-C were multiplied by the slope of the regression line between PS-C (x) and PS-T (y). After correcting for bias, PN measurements from bins 1–3 (0.5–2.0 μm) and 4–5 (2.0–10.0 μm) were summed for analysis to represent fine and coarse modes, respectively.

The largest bin (>10 μm) is excluded from the analysis due to lacking a clear upper size limit and having weaker precision ($R^2 = 0.74$).

3. Results and discussion

3.1. Continuous monitoring of tree stand effects under multiple wind conditions

Wind data directional categories used to assess the near-road impact from the perspective of the sampling locations included: low/variable (wind speed <0.5 m/s, direction variable), downwind (200°–320°),

Table 1

Summary of measurements conducted including measurement parameters, sampling approach and instruments.

Measurement parameter	Sampling approach	Instrument make/model	Sample frequency
Black carbon	Micro-aethalometer	Model AE-51 Magee Scientific	1 s
Particle size and number	Handheld PN sampler	HHPC-6 MetOne	1 min
Latitude and longitude	GPS	VGPS 900 Visiontac Instrument Inc.	1 s
3D wind speed and direction	Ultrasonic anemometer	RM Young Model 8100 V	1 s
Leaf area index	LAI2000	LI-COR Biosciences	–

parallel north (320°–20°), parallel south (140°–200°), and upwind (20°–140°). Some of the analyses combined parallel north and parallel south into a single category to increase sample number. Fig. 3 shows wind roses for the entire study period and for each wind category. For downwind conditions, the majority of the winds occurred from the southwest (210°–230°), while the majority of winds occurred from the northeast (30°–50°) for upwind conditions.

Results from the air quality measurements demonstrated the effect of vegetation on near-road concentrations of coarse and fine particle number (PN) and black carbon (BC). All of the pollutants measured had skewed distributions and were log-transformed for analysis, resulting in normally distributed log-transformed concentrations. After the transformations were computed and time periods isolated to when paired instruments were operating simultaneously, the mean and 95% confidence interval (CI) of the measured concentrations of each pollutant were

calculated for each wind category, then transformed back to their original data scale (Table 2). Fewer measurements were made of BC than of particle counts due to a data logging problem with the micro-aethalometer at PS-T on two of the sampling days.

Black carbon was 12.4% and 7.8% lower behind the vegetation barrier during downwind and parallel wind conditions, respectively. These estimates do not subtract the background; there may be even further reduction of traffic-related BC if background concentrations were known and subtracted. Meanwhile, fine and coarse particle counts did not show significant change during either downwind or parallel wind conditions, i.e. all confidence intervals were overlapping. An analysis of results from past near-road studies found a gradual decrease in $PM_{2.5}$ concentration with distance from the edge of the highway when concentrations were normalized to the edge of the roadway and no relationship when normalized to background (Karner et al., 2010), likely due to the significant background contribution to $PM_{2.5}$ in comparison with the fraction emitted by nearby traffic in many urban areas. In this study, PN background concentrations were not subtracted and likely constitute a significant fraction of the total particles. Although $PN_{2.0-10.0}$ was not significantly different during downwind conditions, the measurement was elevated during upwind periods and may suggest that the vegetation had a trapping effect for local coarse-mode particle emissions from the golf course. However, overall $PN_{2.0-10.0}$ concentrations during upwind periods were lower in comparison to periods of low speed or downwind conditions. Finally, the tree stand did not appear to modify concentrations of any pollutant during low speed wind conditions (<0.5 m/s).

Significant diurnal variation was observed in both PN and BC concentrations (Fig. 4), with the highest average concentrations of particles occurring at the same time as the morning traffic peak (07:00–09:00) and the highest concentrations of BC occurring slightly later and lasting
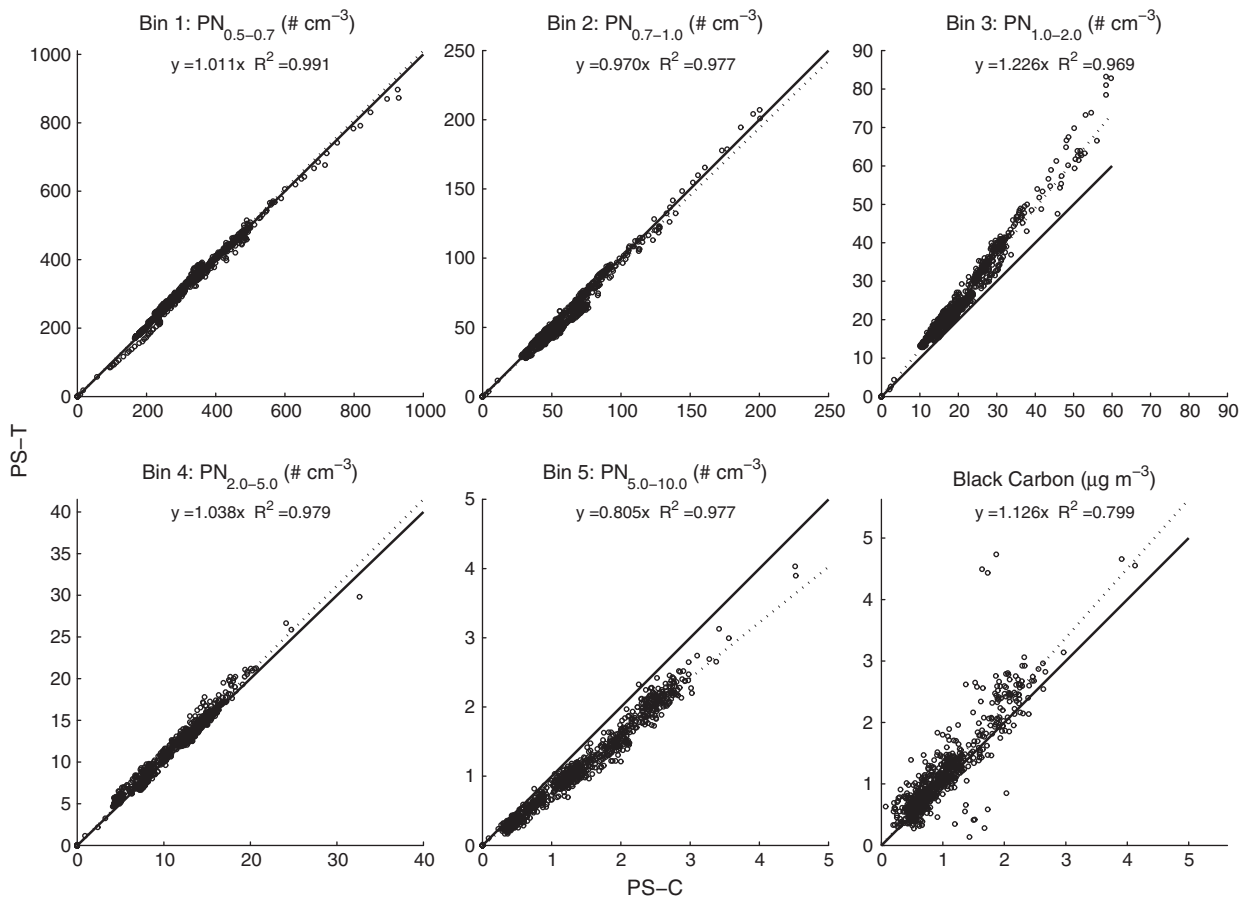

Fig. 2. Comparison of three-minute average collocated PN counts (cm^{-3}) by bin and BC (μg m^{-3}) concentrations. Dashed lines represent the linear regression with intercept set to 0, solid lines represent y = x.
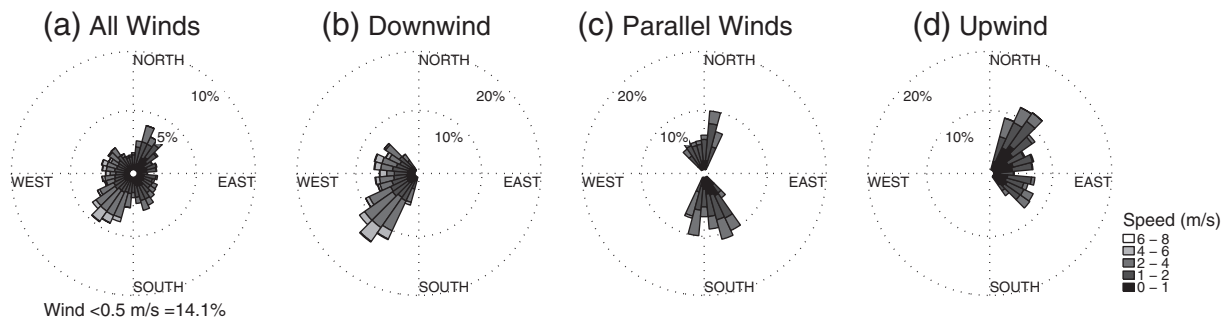
Fig. 3. Wind roses depicting wind speed and wind direction for a) the entire sampling period; b) all winds classified as downwind; c) all winds classified as parallel; d) all winds classified as upwind.

slightly longer (08:00–12:00). The peak in BC corresponds to an increase in wind speed along with an increased percentage of wind from the road, which increases from 24% at 08:00 to 36% at 09:00 and up to 51% by 11:00. Both coarse and fine PN concentrations were also high at night (10:00–03:00), when average wind speeds were ≤1 m/s. While traffic volumes were much lower during this time period, the higher concentrations of coarse particles may have occurred as a result of a greater percentage of trucks operating at higher speeds during the night resulting in more re-entrained road dust generation, with the lower winds allowing for stagnation to occur. The lower wind speeds may also have contributed to higher background concentrations of fine particles. However, lack of fleet specific traffic data and hourly regional PM background concentrations makes it difficult to confirm the cause of these results. BC concentrations remained low at this time. Little to no difference was observed between hourly PN concentrations, either coarse or fine, behind the vegetation barrier when compared to the clearing. Mean BC concentrations, in contrast, were generally higher in the clearing than behind the vegetation. Since no traffic data on fleet mix were available for this study, the influence of light-duty versus heavy-duty vehicle activity on these different pollutant impacts could not be determined.

On account of the strong effect of both wind and traffic, reflected by the hour of day, on PN and BC concentrations, mean concentrations were calculated for three-hour intervals by wind category. The sample size for each of the time intervals with low speed winds between 09:00 and 18:00 for both BC and PN was less than 25, so these time periods are not shown. $PN_{0.5-2.0}$ concentrations did not differ significantly

between sites regardless of wind category or time of day (Fig. 5). The highest concentrations were observed during low-speed winds, which is likely related to slowed dispersion of local emissions and secondary particle formation. $PN_{2.0-10.0}$ concentrations, in contrast, were 13% higher behind the vegetation barrier from 12:00 to 18:00 when upwind of the highway and were 14% lower from 00:00 to 03:00 during low speed winds (Fig. 6). In some cases, the mean PS-T concentration did not fall within the 95% confidence interval (CI) of the mean PS-C concentration or vice versa, but the two sites had overlapping CIs therefore the difference was considered not significant. The higher concentrations behind the barrier during upwind conditions suggest that there may be other upwind sources of large particles such as golf course activities. BC concentrations were significantly lower behind the vegetation barrier from 09:00 to 00:00 when downwind of the highway, with the greatest percent difference occurring between 15:00 and 18:00 when concentrations were 22% lower behind the vegetation barrier (Fig. 7). No difference between the vegetation site and the clearing site was observed during upwind or low speed wind conditions. These findings indicate that the vegetation barrier was able to mitigate a portion of the black carbon emitted by traffic on the nearby highway.

Wind speed is also known to affect particle concentrations (Steffens et al., 2012; Zhu et al., 2002). Comparing the two stationary sites under downwind rush hour (06:00–09:00) conditions, $PN_{0.5-2.0}$ decreases with wind speed, although little to no difference existed between the sites (Fig. 8a). In contrast, $PN_{2.0-10.0}$ and BC concentrations peaked before beginning to decrease at 1.9 m/s and 2.3 m/s respectively

Table 2
Summary statistics by wind category.

Wind category[a]	N	Mean PS-C	95% CI	Mean PS-T	95% CI	% difference (PS-T − PS-C)/PS-C
$PN_{0.5-2.0}$ (cm^{-3})						
Low speed	1440	158	150–167	156	148–165	−1.1% (NS[b])
Downwind	3326	155	151–160	151	147–156	−2.5% (NS)
Parallel	2468	76	72–80	76	72–80	−0.1% (NS)
Upwind	2476	86	82–90	89	85–93	4.3% (NS)
$PN_{2.0-10.0}$ (cm^{-3})						
Low speed	1440	9.2	8.9–9.6	8.6	8.3–9	−6.7% (NS)
Downwind	3326	8.9	8.7–9.1	8.9	8.7–9.1	0.3% (NS)
Parallel	2468	5.5	5.3–5.6	5.7	5.5–5.9	4.4% (NS)
Upwind	2476	5.7	5.5–5.8	6.1	5.9–6.3	8.2% (S[c])
Black carbon ($\mu g\ m^{-3}$)						
Low speed	1201	1.27	1.23–1.31	1.20	1.16–1.24	−5.9% (NS)
Downwind	2762	1.70	1.66–1.74	1.49	1.46–1.53	−12.4% (S)
Parallel	1598	0.93	0.89–0.96	0.85	0.83–0.88	−7.8% (S)
Upwind	1863	0.69	0.66–0.71	0.64	0.62–0.67	−6.0%(NS)

[a] Direction is relative to highway.
[b] NS — not significant difference, 95% confidence intervals overlapped.
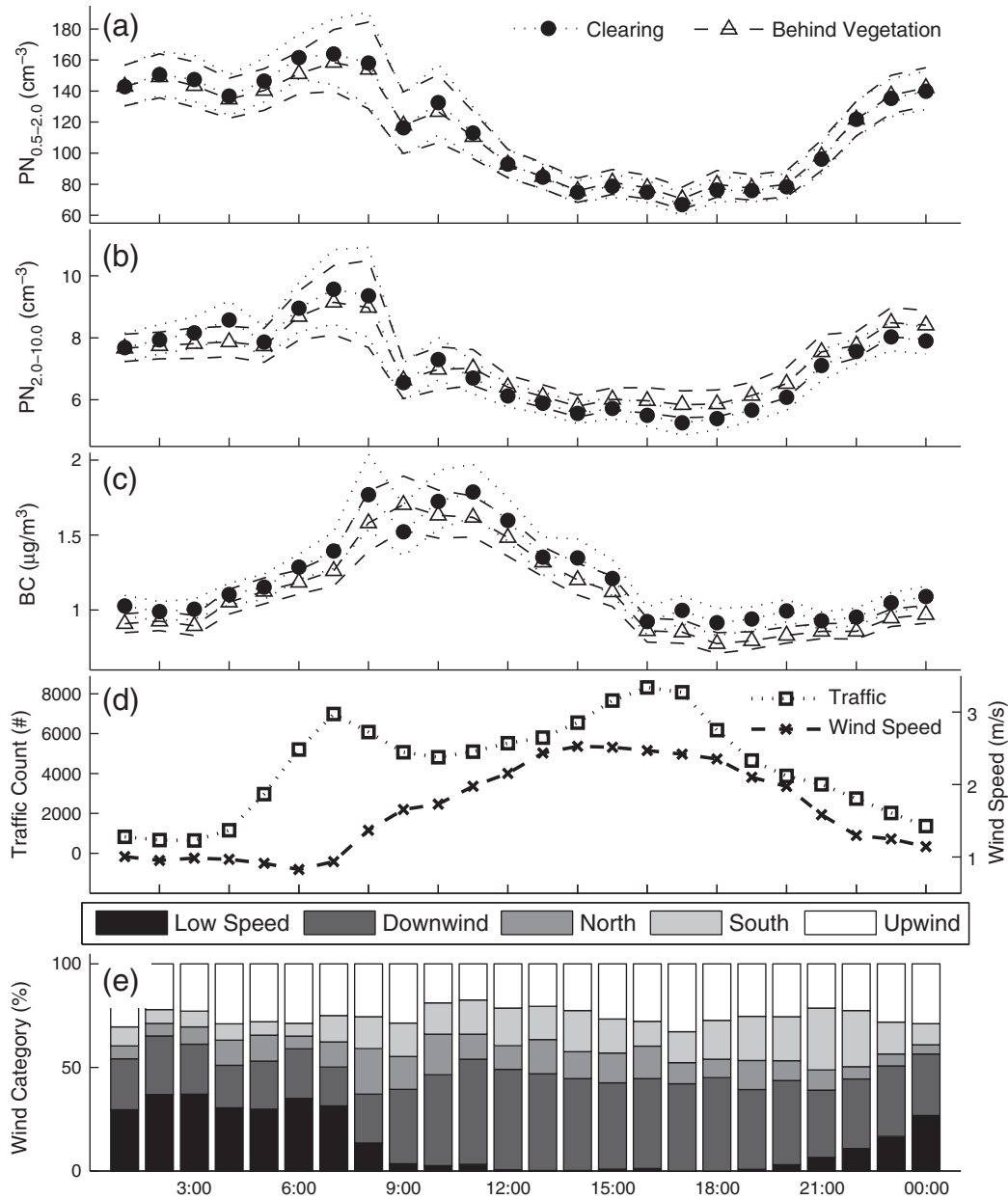[c] S — significant difference, 95% confidence intervals did not overlap.

Fig. 4. Hourly trends in a) $PN_{0.5-2.0}$; b) $PN_{2.0-10.0}$; c) BC; d) traffic activity; and e) wind direction. Lines represent 95% confidence intervals.

(Fig. 8b, c). Like $PN_{0.5-2.0}$, $PN_{2.0-10.0}$ concentrations did not vary significantly between the sites, whereas BC concentrations behind the vegetation barrier were lower than or equal to the concentrations in the clearing at all wind speeds, but the difference was significant only at wind speeds ≤ 1.1 m/s.

3.2. Effects of vegetation barriers on pollutant spatial gradients

Spatial trends in air pollutant concentrations were observed through sequential sampling along a number of sites both in the clearing and behind the vegetation barrier using mobile monitoring. The distance from the highway for these sampling sites ranged from 23 to 104 m and the measured leaf area index (LAI) along the tree stand ranged from 2.6 to 4.7. The LAI values were measured for a series of individual trees selected to represent the range of species constituting the vegetation barrier. The wind speed during the mobile sampling ranged from 0.1 to 5.7 m s^{-1}. The fraction of the mobile sampling data collected behind

the barrier representing downwind or parallel wind conditions (total of 524 three-minute observations, spread over 13 days) was isolated to study downwind spatial gradients. The number of locations in the clearing was limited by the site conditions, therefore only the downwind trends with distance behind the vegetation barrier were examined (Fig. 9). The mean wind speed during downwind mobile sampling was 2.9 m s^{-1} with a standard deviation of 1.1 m s^{-1}.

A clear relationship between BC and distance was observed under downwind conditions that were not present under parallel wind conditions. Although vis-à-vis comparison to unobstructed flow at this site is limited, the attenuation with distance behind the vegetation barrier (36% decrease from 35 m to 90 m) appears to be more gradual than the exponentially decreasing trends previously observed by others in unobstructed areas (54% decrease from 30 m to 90 m) (Zhu et al., 2002).

For this particular site, the vegetation barrier thickness increased along the sequential sampling track. Concentrations with distance would therefore be anticipated to be affected by an increased distance
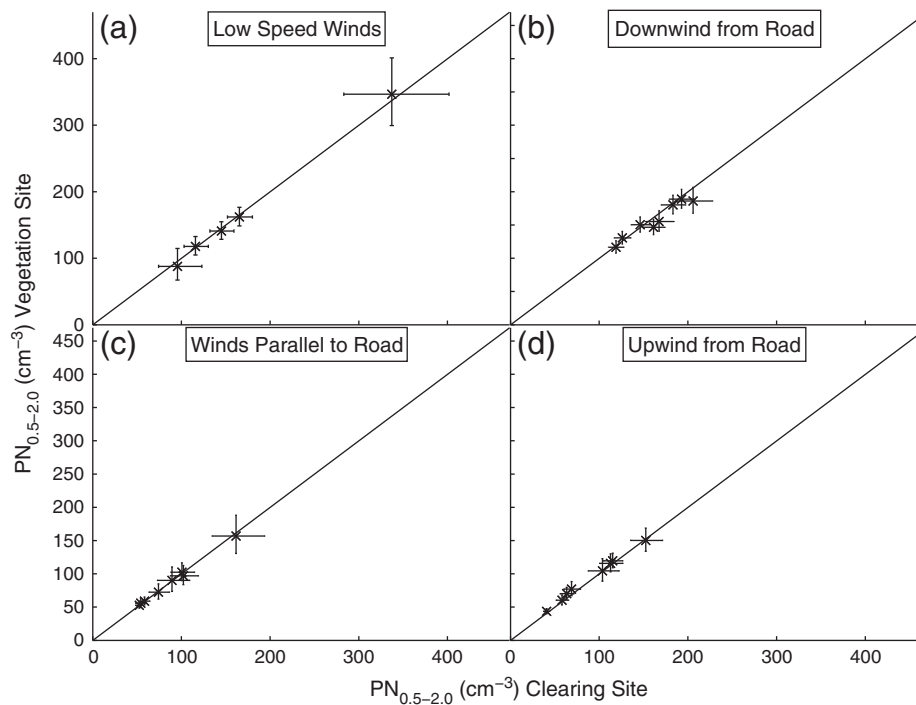
Fig. 5. $PN_{0.5-2.0}$ concentrations by wind category and hour of day in a clearing site and behind a tree stand: a) under low speed wind conditions; b) downwind of road; c) winds parallel to the road; and d) upwind of road. Values shown are means and 95% CIs. Time periods for which the concentration at PS-T is significantly different from PS-C (i.e. non-overlapping CIs) are labeled. Time periods with N < 25 (75 min of data) are not shown. The y = x line is shown for reference.

and an increased thickness of vegetation (Fig. 1), as well as local meteorology. Complicating the situation, a large portion of the downwind conditions occurred from the southwest, an angle that allows air to flow from the highway behind the vegetation stand where the sequential sampling was conducted. Previous studies have found that air flow

perpendicular to a forest edge resulted in recirculation zones in the lee of the forested area, with a flow structure consistent with an intermittent recirculation pattern (Detto et al., 2008; Frank and Ruck, 2008). The lack of a strong downwind attenuation suggests that while the vegetation buffer may reduce near-field concentrations in some areas, it
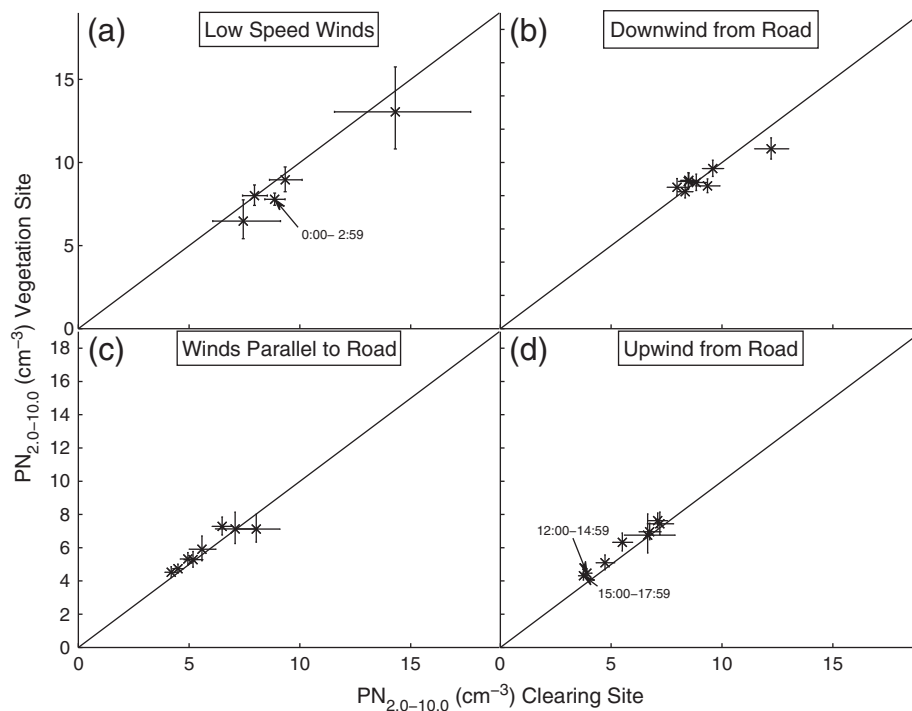

Fig. 6. $PN_{2.0-10.0}$ concentrations by wind category and hour of day in a clearing site and behind a tree stand: a) under low speed wind conditions; b) downwind of road; c) winds parallel to the road; and d) upwind of road. Values shown are means and 95% CIs. Time periods for which the concentration at PS-T is significantly different from PS-C (i.e. non-overlapping CIs) are labeled. Time periods with N < 25 (75 min of data) are not shown. The y = x line is shown for reference.
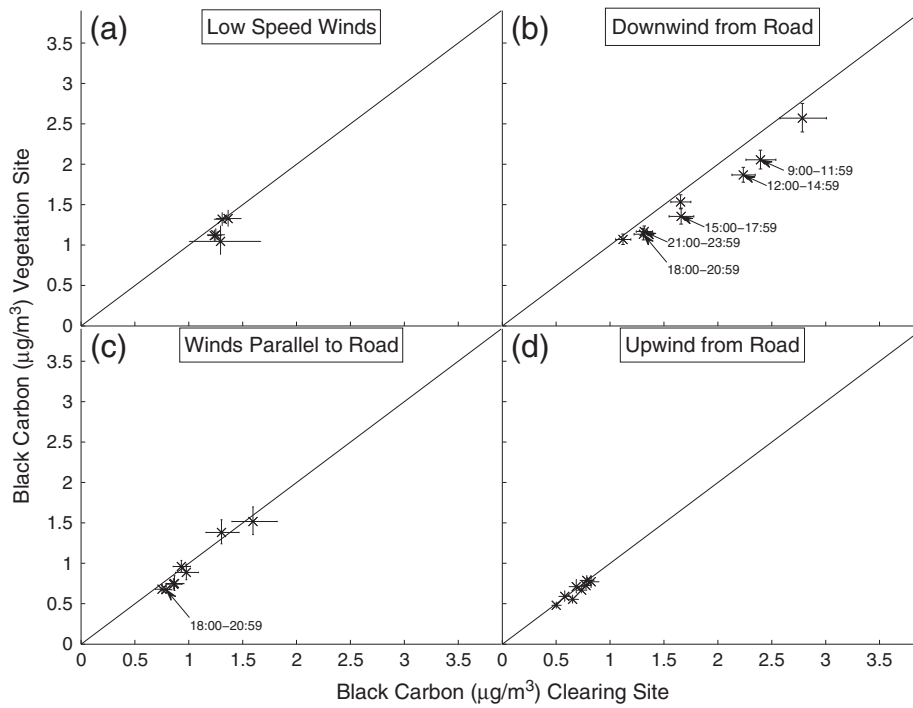
Fig. 7. BC concentrations by wind category and hour of day in a clearing site and behind a tree stand: a) under low speed wind conditions; b) downwind of road; c) winds parallel to the road; and d) upwind of road. Values shown are means and 95% CIs. Time periods for which the concentration at PS-T is significantly different from PS-C (i.e. non-overlapping CIs) are labeled. Time periods with N < 25 (75 min of data) are not shown. The y = x line is shown for reference.

may also create pockets of higher concentrations by slowing downwind dispersion and attenuation as pollutants get caught in the boundary areas along the edges of the barrier.

With a background contribution likely higher than the background contribution of BC, $PN_{0.5–2.0}$ concentrations are stratified by sampling day and show little relationship to distance. $PN_{2.0–10.0}$ concentrations
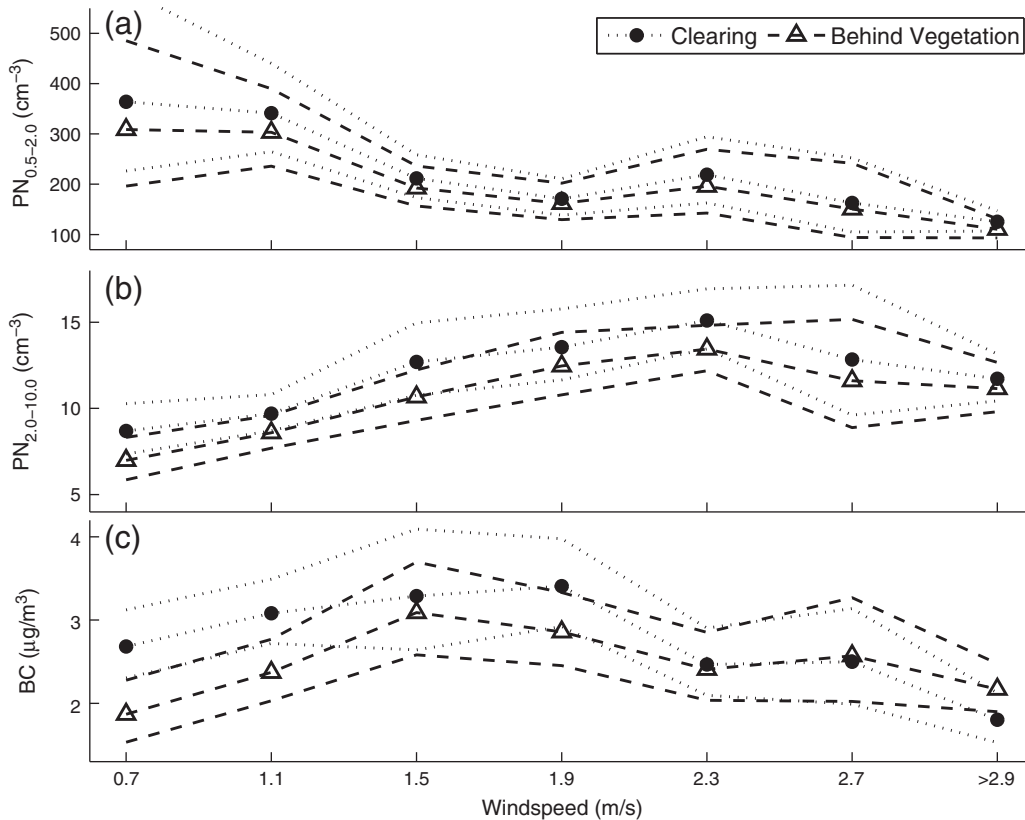

Fig. 8. Concentration in the clearing and behind the vegetation of a) $PN_{0.5–2.0}$; b) $PN_{2.0–10.0}$; and c) BC versus wind speed under downwind conditions. Lines represent 95% CIs.

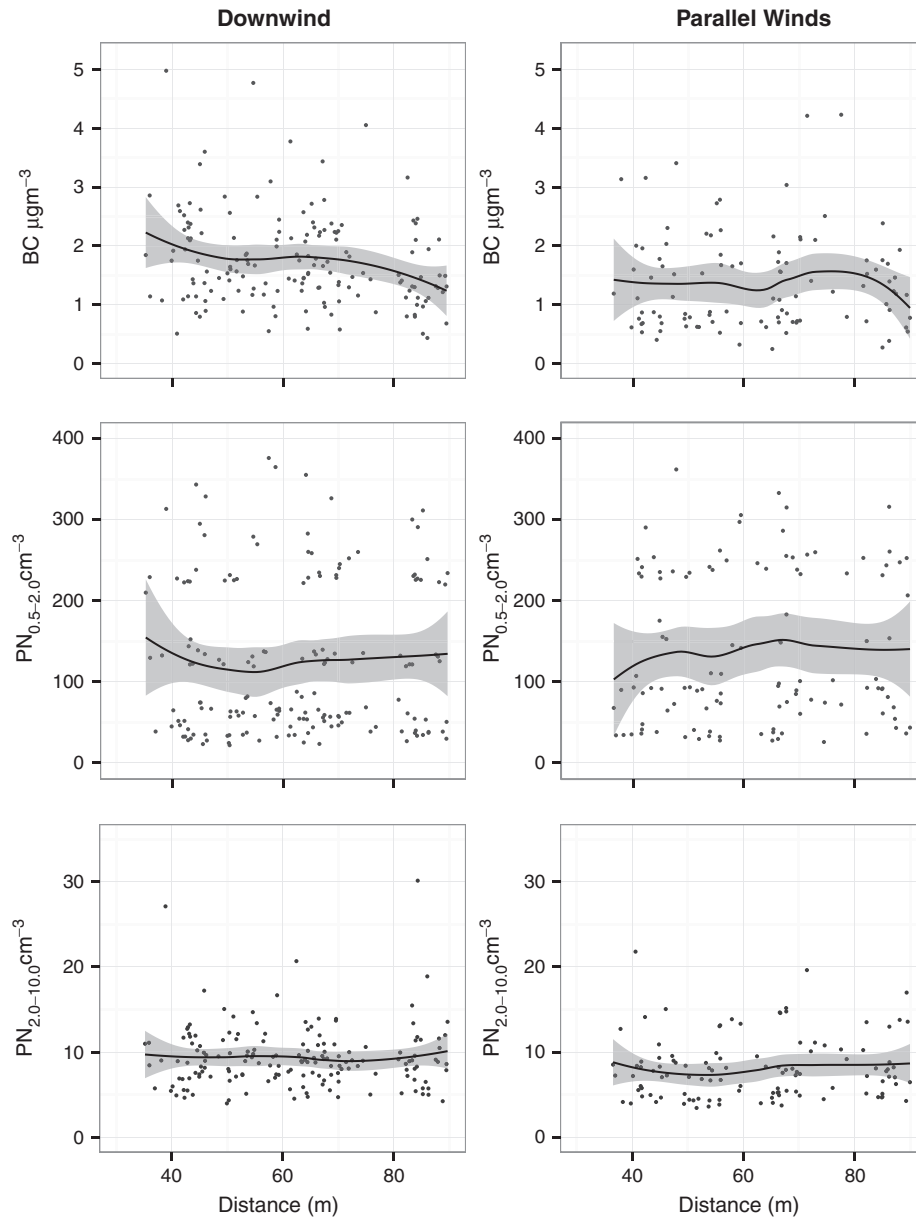**Downwind**   **Parallel Winds**

Fig. 9. Concentrations of BC, $PN_{0.5-2.0}$, and $PN_{2.0-10.0}$ at the sequential sampling sites under downwind conditions (a), (b), and (c), respectively, and under parallel wind conditions (d), (e), and (f). The black line and gray shading represent the conditional mean and 95% CI calculated using a local polynomial regression (loess).

were neither correlated with distance nor as affected by daily variation as $PN_{0.5-2.0}$.

4. Conclusion

As evidence supporting the relationship between near-road air quality and adverse health effects mounts, so does the need for effective methods of mitigating near-road air pollution. The construction of barriers, either solid or vegetative, between roads and populations that will be exposed to traffic emissions is one such method under evaluation since these structures can be constructed in a relatively short time frame. Solid noise barriers have been found to lower near-road (~10 m) mobile-source pollutant concentrations by 25–50% (Baldauf et al., 2008; Finn et al., 2010; Hagler et al., 2011, 2012; Ning et al., 2010). Noise barriers surrounded by vegetation have been found to reduce UFP concentrations more than a noise barrier alone at distances ranging from 20 to 300 m from the road (Baldauf et al., 2008). While vegetation is known to intercept airborne particles, the results of a

previous field study that investigated the effects of vegetation barriers on near-road air quality werevariable, with behind-barrier UFP levels higher at some times and lower at others than levels observed in a nearby clearing (Hagler et al., 2012). The past field study by Hagler et al. (2012) utilized a vehicle-based mobile monitoring strategy, in which the roadway network limited sampling to a single distance from the road and the sampling was discontinuous.

The current study illustrates the importance of accounting for both meteorological conditions such as wind speed and direction as well as diurnal trends when determining the effect of barriers. Continuous sampling revealed reductions in BC behind the vegetation barrier during downwind (12.4%) and parallel (7.8%) wind conditions, with maximum reductions up to 22% in the late afternoon with winds from the road. $PN_{0.5-2.0}$ levels, in contrast, were not significantly different behind the vegetation barrier regardless of wind conditions or time of day. Concentrations of $PN_{2.0-10.0}$ were lower behind the vegetation barrier during low speed (<0.5 m s^{-1}) winds, while concentrations were sometimes higher during upwind conditions. Note that this study occurred during

spring and summer months, with maximum leaf area for deciduous trees and brush. Results are anticipated to be different during winter months (Hagler et al., 2012).

This study is also the first field study to investigate the effect of the width of a vegetation barrier. The mobile measurements suggest that the dimensions and configuration of the vegetation influences the extent of pollutant reductions. The lack of strong downwind BC attenuation with an increase in both the width of vegetation and distance from the road suggests that, while vegetative buffers may reduce near-field concentrations, the recirculation zones downwind of buffers may slow dispersion and attenuation, resulting in areas with concentrations higher than what might occur if the vegetation was not present. For this study, the triangular shape of the vegetation stand may have allowed pollutants to enter through the clearing sections and transport and collect behind the vegetation stand. Thus, these results show the importance of the vegetation configuration, and may not reflect the concentration differences for a continuous vegetation stand with similar depths. Furthermore, it cannot be determined from the current study whether areas farther away from the vegetation barrier, outside of the recirculation zone, experience further reductions in pollutant concentration when compared to a no-barrier case. Additional research is warranted to understand the effect of vegetation barriers of varying widths and to separate the effects of vegetation from the effects of distance.

Vegetation in urban settings can provide numerous benefits beyond air quality improvements; including temperature and stormwater regulation, noise moderation, and esthetic improvements. The results of this study indicate that vegetative barriers may modestly improve near-road concentrations of PM primarily emitted from traffic sources (as represented by BC); however, the recirculation zones downwind, caused by gaps and other boundary edge effects, may result in areas of increased pollution compared to a no-barrier case. The results of this and other studies highlight the complexity and need for careful design of the vegetation barrier to optimize benefits and reduce the potential for unintended consequences.

5. Disclaimer

This document has been reviewed in accordance with the U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. The views expressed in this journal article are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

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