DUST REDUCTION EFFICIENCY OF A SINGLE-ROW VEGETATIVE BARRIER (*MACLURA POMIFERA*)

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ABSTRACT. *Little is known about the dust removal efficiency of common vegetative barriers. This study of blowing dust reduction was conducted on one of the most common vegetative barriers used for wind erosion control in Kansas and the U.S. Great Plains, the deciduous tree species* Maclura pomifera *(Osage orange). A dust generator and distributor were fabricated to generate dust particles for determining the dust removal efficiency of a single-row Osage orange barrier. Simultaneous upwind and downwind dust concentrations were measured using mini-vol samplers for total suspended particulates (TSP) at heights of 1.5, 3.0, 4.5, and 6.0 m above the ground. Measurements were made using two towers located at upwind and downwind distances equal to the height of the barrier. Particle size distribution (PSD) analysis of the initial generated dust showed that most particles were large (GMD = 102.8 μm), while about 5% of the dust was particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) and 15% was less than 10 μm (PM_{10}). Laser diffraction analysis of particles from the sample filters was used to determine the dust reduction efficiency of the barrier. Results showed that dust reduction was significantly related to reduction in wind speed at lower heights, causing an overall decrease in dust concentration as particles passed through the barrier. Concentrations of larger particles (~100 μm) were also reduced relative to smaller particles when dust passed through the barrier. The data also showed that 4.5 m above the ground, near the crown of the canopy, was most efficient at removing the $PM_{2.5}$ (15% to 54%) and PM_{10} (23% to 65%) fractions of the generated dust.*

Keywords. *Generated dust, Osage orange, $PM_{2.5}$, PM_{10}, TSP, Wind erosion.*

Agricultural lands that are exposed to dry, windy conditions are susceptible to wind erosion. Vegetative barriers (also called windbreaks or shelterbelts) of single or multiple rows of trees are typically planted to prevent or minimize wind speeds to reduce soil erosion. Vegetative barriers are beneficial aesthetically (Grala et al., 2010) and for reducing wind speed downwind of the barrier. Barriers also cause changes in the soil microclimate (Cleugh, 1998) and affect crop yields (Kort, 1988; Bird et al., 1992; Sudmeyer et al., 2002; Osorio et al., 2018), livestock health (Mader et al., 1999), and home gardens (Ffolliott, 1998). Vegetative barriers can also mitigate odor (Tyndall and Colletti, 2007), sound (Ozer et al., 2007), spray drift (Lazzaro et al., 2008; Vischetti et al., 2008), and air pollutant emissions (Kulshreshtha et al., 2009; Brantley et al., 2014).

Previous studies have assessed the effects of vegetative barriers on airflow (Hagen and Skidmore, 1971; Fryrear and Skidmore, 1985; Gregory, 1995; Brandle et al., 2004; De Zoysa, 2008; Guo, 2008; El-Flah, 2009) and particulate matter (PM) mitigation (Grantz et al., 1998; Dierickx, 2003; Burley et al., 2011; Lin and Khlystov, 2012). Using an efficient sampling methodology, Tiwary et al. (2008) evaluated the effectiveness of an unspecified Hawthorn hedge species for removing ambient PM using two gravimetric PM_{10} (PM with equivalent aerodynamic diameter of 10 μm or less) samplers placed ~1.3 m upwind and downwind at a height of approximately 70% of the barrier height, near the crowns of the trees. Their study quantified the filtration collection efficiency of the Hawthorn trees, which they found to be 30% to 38% of ambient PM_{10}.

Complexity of the flow within the tree canopy is important (Raupach et al., 2001). Complex flow through the canopy results in great turbulence as vegetative elements hinder the incoming flow and initiate tortuosity and effective mixing of PM (Tiwary et al., 2008). Details of flow through the canopy differ for various species because the elements that comprise them differ, such as their aerodynamic characteristics. Most vegetative barrier species are not documented with respect to their ability to reduce wind and remove or

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mitigate PM within their surroundings. Although Osage orange trees are commonly used as wind barriers throughout the U.S. Great Plains, their effectiveness in PM mitigation has not been quantified. The objective of this study was to quantify the effects of a single-row Osage orange barrier for dust removal. Specific objectives were to:

1. Determine the effects of an Osage orange barrier at various heights on windborne particle size distribution (PSD).
2. Determine the percentage reduction in particle concentration ($C_{Reduction}$) at various heights of the Osage orange barrier.

Materials and Methods

Site Description

This research was part of a larger study that also investigated the effects of the same vegetative barrier on optical porosity and drag under leaf-on and leaf-off conditions (Gonzales et al., 2018). Experiments in which dust was collected in three replicates on three different days were conducted from August 2014 to September 2014 at a field site near Riley, Kansas (39° 18′ 49.1″ N 96° 54′ 29.2″ W). The experimental site, located at an elevation of 580 m, was 300 m in length and 200 m in width. The vegetative barrier bisected the field and ran from east to west, with upwind on the south side and downwind on the north side (fig. 1). The field was planted with a winter wheat, corn, and sorghum rotation. No-till management was used to maintain soil productivity and decrease vulnerability to erosion. The barrier consisted of a single row of Osage orange (*Maclura pomifera* (Raf.) Schneid.) trees with leaves present, providing an optical porosity of 22.5% ±0.7%. The barrier measured 2.5 m in width with an average height (H) of 8.5 ±0.6 m. During the experiments, both sides of the field had wheat stubble cut to a height of approximately 0.1 m.

The prevailing wind direction at the field site is south-southwest in summer and north-northwest in winter. Data were collected with a direct south wind. The upwind fetch to the south was assumed to be 150 m because the vegetation was different beyond that point, as can be seen in figure 1. The 150 m fetch should be sufficient for the wind profile to fully develop and stabilize before reaching the barrier. Vegetation was uniform to the north and south of the barrier within 150 m of the barrier. The field slope was <1% in the direction of the wind during the tests.

Dust Generation

To measure the dust reduction efficiency of the barrier, a dust line source was used. Dust particles were obtained by grinding a silt loam soil (25% clay, 9% sand, and 66% silt) in a mechanical grinder after drying in an oven for at least 24 h at 60°C. A fluidized bed dust generator was developed to disperse dust particles into the air. The generator consists of a screw-type feeder, centrifugal blower, electric motor, and dust outlet (fig. 2). The feeder has control settings to emit the desired amount of dust. The centrifugal blower, powered by the electric motor, forces air through a bed of dust particles and moves the generated dust to the dust outlet (Prenni et al., 2000).

A dust distributor (fig. 2) was designed and fabricated from PVC pipe and was connected to the dust generator to provide eight point sources approximately 0.9 m apart, each pipe with 5.4 cm inside diameter. The dust distributor was designed to have approximately equal pressure drop from the pipes for all emission points, producing equal dust emission and concentrations across all emission points. Sudden but

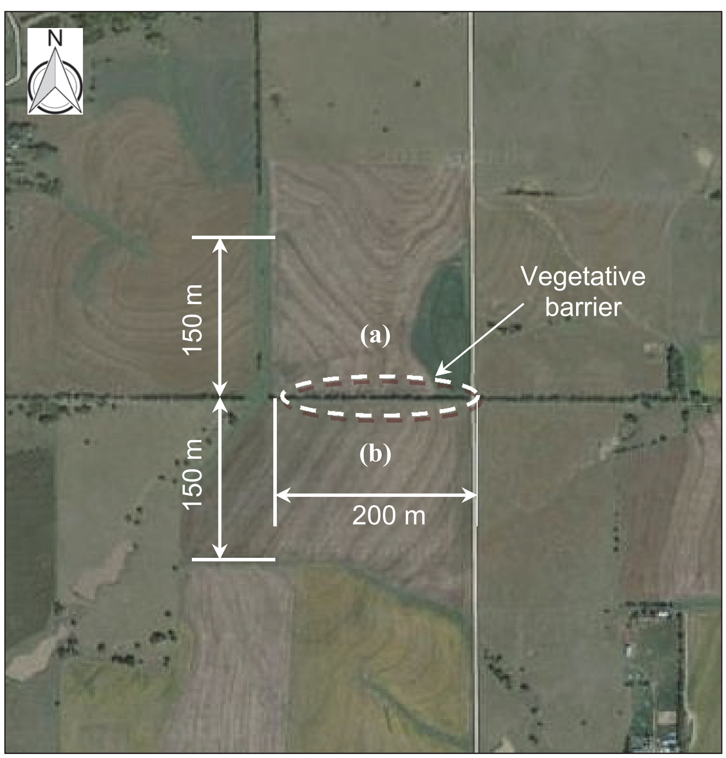

Figure 1. Aerial view of field site (from Google Maps, https://maps.google.com) with barrier test section: (a) north side and (b) south side.

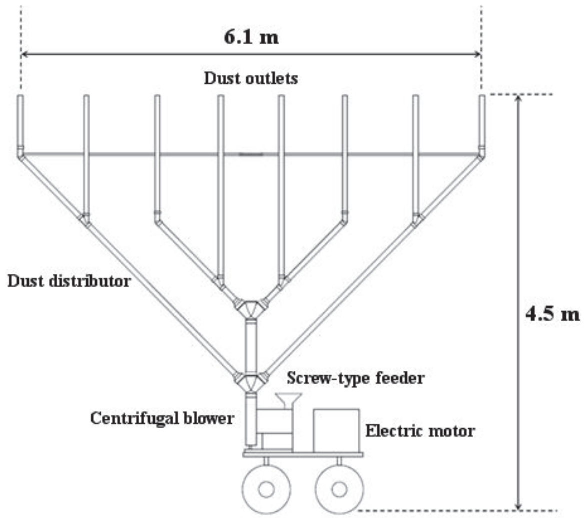

Figure 2. Dust generator designed for this study.

minor shifts in wind direction sometimes occurred during the experimental runs; at such instances, the dust distributor was moved to ensure that the dust source remained aligned with the upwind and downwind samplers. The 6.1 m width of the distributor also allowed easy alignment of the dust distributor with the measurement equipment. Preliminary tests with the dust distributor were successful in generating measurable amounts of dust upwind and downwind of the barrier, and it was therefore used for the remainder of the tests.

Field Sampling

Upwind and downwind wind profiles for the Osage orange barrier were obtained concurrently with total suspended particulates (TSP). The sampling layout is shown in figure 3. Towers were positioned approximately 1*H* from both sides of the barrier in the middle of the 200 m barrier section (fig. 1). This distance was chosen to prevent effects of recirculation regions before and after the Osage orange barrier that could induce particle re-entrainment and affect measured particle concentrations (Huang et al., 2005). Anemometer and PM sampler heights of 1.5, 3.0, 4.5, and 6.0 m above the ground (fig. 4) were based on the methodology used by Tiwary et al. (2008) and Sellier et al. (2008). TSP samplers were mounted at the same heights as cup anemometers (Sierra Misco 1005 DC, NovaLynx Corp., Grass Valley, Cal.) (fig. 4) on each tower at the north and south sides of the barrier.

TSP was collected using identical PM samplers (Mini-vol TAS, Airmetrics, Springfield, Ore.) equipped with TSP inlets using a constant sampling flow rate of 5 L min^{-1}. Due to restrictions on the maximum feed rate of the samplers and the amount of sample required for laser diffraction analysis, all tests were run for 1.5 h, which was time enough to collect an appropriate amount of dust for PSD analysis. The sampling technique followed that of Tiwary et al. (2008), except that three additional samplers (a total of four samplers per tower) were placed at the various heights, with the topmost sampler near the crown of the barrier.

The polytetrafluoroethylene (PTFE) filters used for sampling were conditioned for 24 h at 25°C and 40% RH in a chamber prior to weighing, before and after sampling, for mass determination of dust particles (Cavanagh et al., 2009; Gonzales et al., 2012). The mass of dust collected was the difference in the mass of the conditioned filter before and after sampling, while concentrations were derived by dividing the mass of dust collected by the total volume of air sampled and then recorded by the PM sampler.

Particle Size Distribution Analysis

The ground soil used as the dust source was analyzed using wet analysis on a laser diffraction particle size analyzer (LS-13320, Beckman Coulter Life Sciences, Indianapolis, Ind.), as described by Gee and Or (2002). The PSD of the dust is shown in figure 5. Large particles dominated, as evidenced by the skewness of the plot toward larger sizes. The geometric mean diameter (GMD) of the dust was 102.8 µm, with a geometric standard deviation (GSD) of 5.2.

Uniformity of the dust was ensured during the grinding

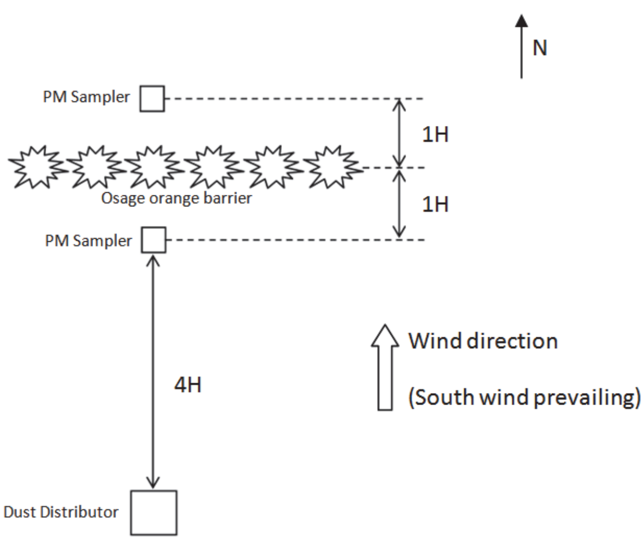

Figure 3. Experiment layout showing locations of PM samplers and dust distributor relative to Osage orange barrier (*H* = 8.5 m).

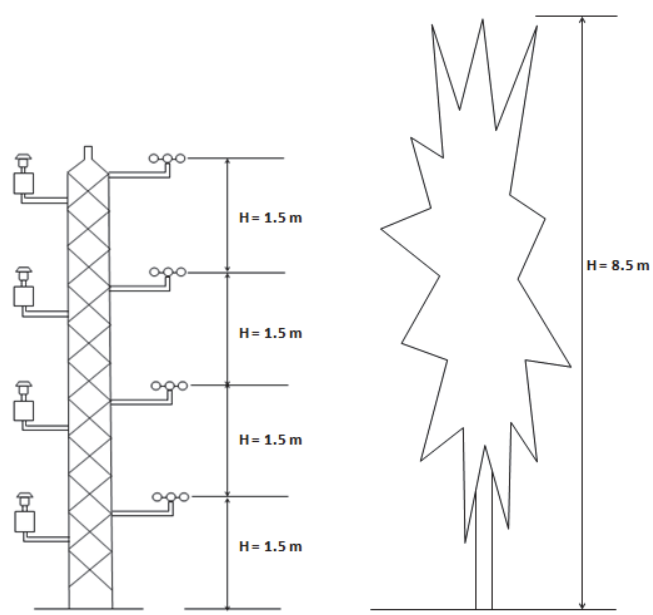

Figure 4. Heights of TSP samplers and cup anemometers relative to the barrier height. The samplers and anemometers and were aligned perpendicular to the wind direction (i.e., not as shown), so the wind was not obstructed between one instrument and another.

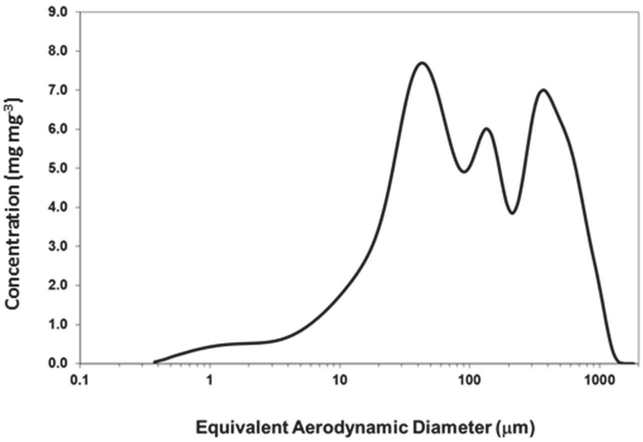

Figure 5. Particle size distribution of dust that was fed through the dust generator.

process by making sure no soil was left in the grinding machine, which could happen if the soil was somewhat moist. Preliminary dust generation tests showed that the dust tended to re-aggregate due to air humidity after soil passed through the grinder. The soil used for dust generation was therefore dried at 60°C for 48 h and kept in sealed plastic containers until field use.

The sampled dust particles were also characterized using the laser diffraction particle size analyzer. Dust collected in the filters was washed using isopropyl alcohol and placed in plastic 50 mL centrifuge tubes. A vortex mixer was used to keep the particles dispersed.

The GMD and GSD of the source dust were obtained using discrete laser diffraction size data, and PM_{10} and $PM_{2.5}$ concentrations were estimated using the particle fraction method (Gonzales et al., 2012). Aerodynamic diameters were obtained using an aggregate density of 1.4 ±0.1 g cm^{-3}, identical to that of Gonzales et al. (2012). Estimated $PM_{2.5}$ comprised 5% of the source dust, and PM_{10} comprised 15%. Based on the dust concentrations upwind and downwind of the Osage orange barrier, the particle concentration reduction ($C_{Reduction}$), which was similar to the collection efficiency of filtration from previous studies (Tiwary et al., 2005, 2008), was computed using the following equation:

$$C_{Reduction} = \frac{c_{up} - c_{down}}{c_{up}} \quad (1)$$

where C_{up} and C_{down} are the dust concentrations (μg m^{-3}) upwind and downwind, respectively, of the Osage orange barrier.

Data Analysis

Mean values of mass concentrations were obtained from each of the four PM sampler heights (representing the various height levels on each tower) using three replicates (i.e., three separate days) for each sampling location (i.e., upwind and downwind). The filter dust samples were used for laser diffraction analysis. Statistical analysis on wind speed reduction and dust reduction efficiency was performed using Microsoft Excel (Microsoft Corp., Redmond, Wash,). Analysis of variance (ANOVA) and paired t-tests were used to determine differences in mass concentrations, wind speed reduction, GMD, and $C_{Reduction}$. CurveExpert 1.4 (Hyams, 2013) was used to plot best-fit curves that were compared to the curve fitting tool in Microsoft Excel.

Results and Discussion

Particle Size Distribution

Figure 6 shows the PSD of sampled dust at various heights for the two locations (upwind and downwind of the barrier). Large particles were dominant (represented by higher concentrations) at the lower level (level 1 at 1.5 m above the ground), while small particles were dominant at the highest level (level 4 at 6.0 m above the ground) for both locations. In general, reductions in large particles occurred, as indicated by the shift of the plots toward the left (toward small particle sizes) and reduced concentrations for large particle sizes. This trend was more pronounced for the lower levels (levels 1 to 3), as evidenced by the sharp decrease in size, where all three plots are skewed toward small particles. Although large particles were also removed at the upper level (level 4), the PSD changes were not as pronounced as the other levels. It should be noted that the upwind concentrations at level 4 were lower than at the other three levels.

Table 1 summarizes the GMD values for the various heights. The GMD values for the uppermost levels (levels 3 and 4) upwind of the barrier were significantly different ($p < 0.05$) from the GMD values of the two lower levels. This was expected because the dust was distributed vertically into the air 4.5 m above the ground, in line with the PM sampler at level 3, and the upwind samplers were located 4*H* away from the dust source (figs. 3 and 4). Large particles were not expected to dominate at the topmost sampler level (level 4) because those particles were expected to have settled, as explained by Lundgren et al. (1984) and shown in figure 7. However, no significant differences ($p < 0.05$) were observed in the GMD values between various heights downwind of the barrier, indicating that most of the large particles that dominated the lower three levels upwind of the barrier were removed by the barrier. Significant differences ($p < 0.1$) were found between upwind and downwind GMD values at levels 1 and 2 only, as larger particles apparently settled to lower levels more rapidly, as expected, both before and after passing through the barrier.

Figure 8 shows the relationship between wind speed and GMD at different heights. Based on Gonzales et al. (2012), GMD was expected to increase as wind speed increased. In this study, the expected trend was observed for all heights, i.e., a decrease in GMD of the suspended particles occurred at lower wind speeds (Jones et al., 2010; Lundgren et al., 1984). This occurred because large particles settled faster than small particles, even over a short distance. At higher wind speeds, large particles remained suspended longer, resulting in increased GMD.

Measurement of Dust Concentrations and Concentration Reductions

The measured concentrations summarized in table 2 are

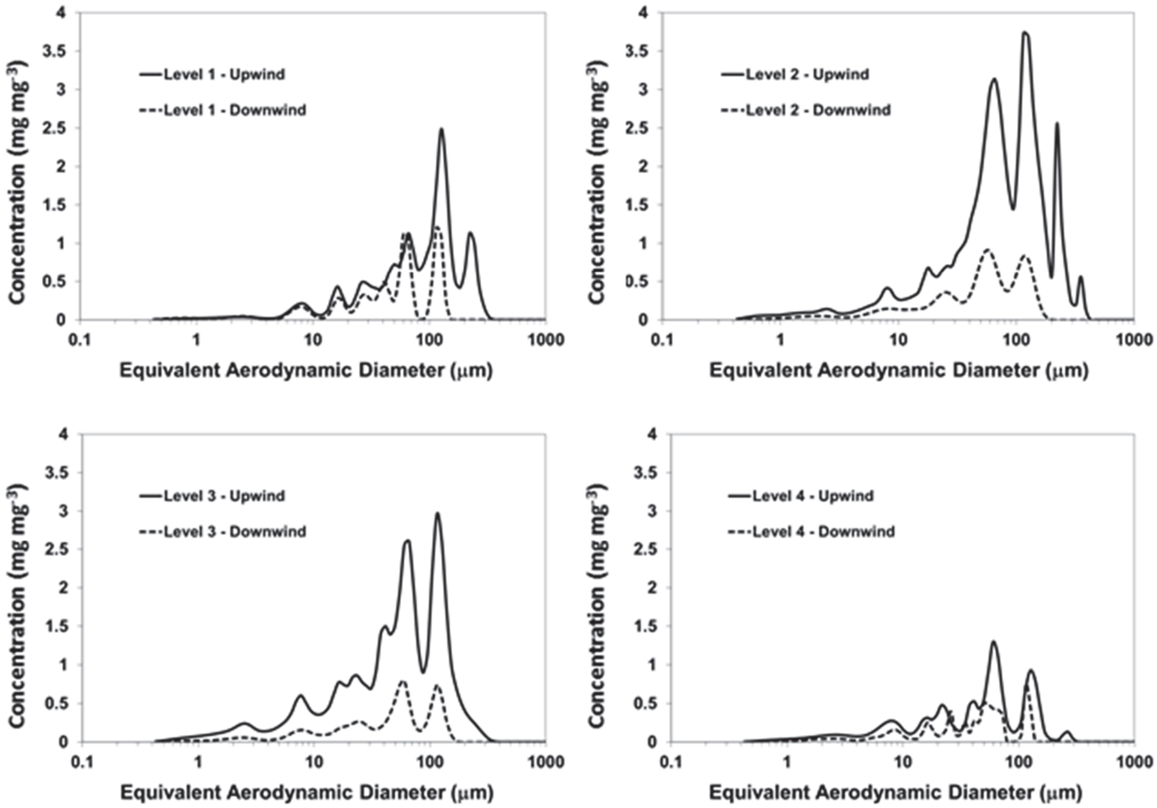

Figure 6. Particle size distribution at specific heights: level 1 = 1.5 m, level 2 = 3.0 m, level 3 = 4.5 m, and level 4 = 6.0 m above the ground.

Table 1. Mean geometric mean diameter (GMD), geometric standard deviation (GSD), and standard error of the mean (SEM) of particles at various heights upwind and downwind of the Osage orange barrier (three replicates).[a]

Level	Height above Ground (m)	GMD ±SEM (µm)		GSD ±SEM	
		Upwind	Downwind	Upwind	Downwind
1	1.5	65.6 ±7.8 Aa	44.6 ±0.5 Ab	3.2 ±0.7 Aa	3.6 ±0.1 Aa
2	3.0	61.4 ±10.3 Aa	40.3 ±4.4 Ab	3.5 ±0.2 Aa	3.6 ±0.1 Aa
3	4.5	49.3 ±12.9 Ba	38.3 ±0.9 Aa	4.0 ±0.2 Aa	3.9 ±0.1 Aa
4	6.0	34.4 ±5.9 Ba	34.4 ±4.0 Aa	4.3 ±0.2 Aa	3.7 ±0.3 Aa

[a] Means followed by different letters are significantly different: uppercase letters indicate differences between heights within a column ($p < 0.05$), and lowercase letters indicate differences between upwind and downwind GMD and GSD values ($p < 0.1$).

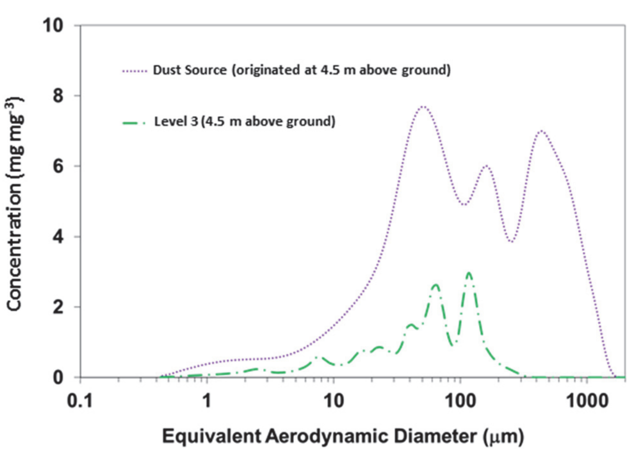

Figure 7. Particle size distribution collected at the dust source and at 4*H* downwind of the dust source (i.e., just upwind of the barrier).

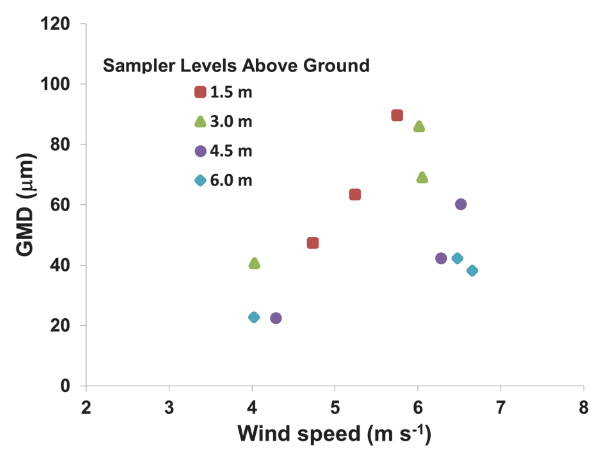

Figure 8. Relationship between average GMD of collected dust and wind speed at various heights for three different sampling days.

not representative of the local ambient dust concentrations and were therefore used to compute the reduction efficiency of the Osage orange barrier. In addition, a correction factor derived from PM concentration values with and without a downwind barrier was introduced to compute the dust concentration reduction efficiency of the Osage orange barrier, similar to the approach used by Tiwary et al. (2008). Mass concentrations of $PM_{2.5}$ and PM_{10} were determined downwind of the source without the barrier, and the corresponding decreases were the correction factors used for computing the

Table 2. Mean mass concentrations ± standard error of the mean of $PM_{2.5}$, PM_{10}, and TSP upwind and downwind of the barrier.[a]

Level	Height above Ground (m)	Mean Mass Concentrations ($\mu g\ m^{-3}$) $PM_{2.5}$ Upwind	$PM_{2.5}$ Downwind	PM_{10} Upwind	PM_{10} Downwind	TSP Upwind	TSP Downwind
1	1.5	145 ±25 Aa	123 ±14 Aa	483 ±84 Aa	374 ±36 Aa	10815 ±2260 Aa	8017 ±368 Aa
2	3.0	226 ±31 Aa	146 ±27 Ab	779 ±74 Ba	479 ±65 Ab	14042 ±2358 Aa	8952 ±302 Ab
3	4.5	288 ±54 Aa	131 ±23 Ab	825 ±200 Ba	460 ±78 Aa	16331 ±3076 Aa	6056 ±693 Aa
4	6.0	136 ±47 Ba	102 ±37 Aa	516 ±158 Aa	360 ±127 Aa	10417 ±2500 Aa	7523 ±698 Ab
Average		199 ±39 a	126 ±25 a	651 ±129 a	418 ±77 a	12901 ±2549 a	7637 ±515 b

[a] Means followed by different letters are significantly different: uppercase letters indicate differences between heights within a column ($p < 0.05$), and lowercase letters indicate differences between upwind and downwind values for each size class ($p < 0.1$).

concentration reduction efficiency. The dust generated from the ground soil was tested for $PM_{2.5}$ and PM_{10} and was found to have correction factors of 1.9% and 5.8%, respectively.

From the values in table 2, the largest reductions in $PM_{2.5}$ and PM_{10} corresponded to the largest decreases in TSP. These occurred mainly at level 3 (4.5 m above the ground), followed by level 2 (3.0 m above the ground). Level 3 also differed significantly ($p < 0.02$) from the $C_{Reduction}$ of the other levels (table 3). The lower values measured at the two lower levels (levels 1 and 2 at 1.5 and 3.0 m above the ground, respectively) could be due to gaps in the lower portions of the barrier (fig. 9). The lower concentrations near the ground are likely due to settling of the emitted dust particles before reaching the sampler. The presence of gaps in the barrier should divert some of the upper flow downward and thus help increase the settling of particles. Intermittent changes in wind direction during sampling could potentially cause some of the source dust to drift away from the samplers. The highest value of $C_{Reduction}$ occurred at level 3 (table 3), corresponding to a location in the barrier where significant vegetation was present to filter out dust particles (Gonzales et al., 2018). However, level 4 was closest to the canopy crown and did not show the same high reduction efficiency. This is possibly due to the height of the dust source (i.e., 4.5 m, close to level 3). Because level 4 was close to the canopy crown, it is assumed that a portion of the dust passed above the barrier, and thus the reduction at level 4 was less than at level 3.

Table 3. Comparison of wind speed reduction with PM reduction efficiency.[a]

Level	Height Above Ground (m)	Wind Speed Reduction (%)	$C_{Reduction}$ (%) $PM_{2.5}$	PM_{10}	TSP
1	1.5	20.6	15.4 Aa	22.6 Aa	25.9 Aa
2	3.0	30.7	35.8 Aa	38.5 Aa	36.2 Aa
3	4.5	37.8	54.4 Ba	65.4 Ba	62.9 Ba
4	6.0	54.6	24.9 Aa	30.2 Aa	27.8 Aa
Average		35.9	32.6	39.1	38.2

[a] Different letters indicate significant differences ($p < 0.02$) between rows within a size class (uppercase letters) and between columns (lowercase letters).

Figure 9. Osage orange barrier used for the experiments. This windbreak would be rated as good condition (USDA-NRCS, 2010).

Table 3 shows the wind speed reductions at the same heights as the PM samplers as compared to the reduction efficiencies of $PM_{2.5}$ and PM_{10}. At the three lowest levels, greater reduction in wind speed by the Osage orange barrier corresponded to greater dust removal by the barrier. However, level 4 (6.0 m) did not exhibit this trend, even though it represented the canopy crown, possibly due to insufficient suspension (upward diffusion) of dust that originated 4.5 m above the ground (fig. 2). Because the values in table 2 were assumed to not include significant concentrations of ambient dust, the average PM_{10} reduction efficiency of the Osage orange barrier was comparable to the performance of the Hawthorn hedge tested by Tiwary et al. (2008), where the collection efficiencies ranged from 30.4% to 38.1%.

CONCLUSIONS

A dust generator was fabricated and connected to a dust distributor to simulate a line source of dust and assess the dust reduction efficiency of an Osage orange barrier. Ground soil (GMD of 102.8 μm and GSD of 5.2) was used as the source dust, which was composed of 5% $PM_{2.5}$ and 15% PM_{10}. Results showed that a single row of Osage orange trees removed 15% to 54% of $PM_{2.5}$, 23% to 65% of PM_{10}, and 26% to 63% of TSP from the generated dust. The maximum reduction of dust particles occurred near the crown of the tree canopy. The average dust reduction efficiency of the Osage orange barrier was 33% for $PM_{2.5}$, 39% for PM_{10}, and 38% for TSP. The PM_{10} reduction was comparable to that reported in a previous study of a Hawthorn hedge (30.4% to 38.1%; Tiwary et al., 2008). In addition, PSD analysis using laser diffraction showed that, upwind of the barrier, larger particles were removed by the lower portion of the barrier, while smaller particles dominated the dust removed from the upper level samplers. Downwind of the barrier, PSD analysis generally showed a decrease in GMD values at all heights (1.5, 3.0, 4.5, and 6.0 m), indicating that the Osage orange barrier removed passing dust particles, especially large particles. However, smaller particles of $PM_{2.5}$ and PM_{10} size were removed most efficiently near the canopy crown at 4.5 and 6.0 m above the ground.

The dust reduction efficiencies obtained in this study would be useful for numerical analysis validation in examining the flow of particulate matter through a specific vegetative barrier like Osage orange trees. Further research is needed to determine how dust reduction is affected by multi-row barriers, various levels of foliage, and the corresponding aerodynamic properties of deciduous trees such as Osage orange.

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