A wind-tunnel study of the effect of turbulence on PM_{10} deposition onto vegetation

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Abstract

The fraction of particles deposited from an airstream (deposition fraction) onto idealized substrates has been shown to be influenced by isotropic turbulence through increased deposition onto nonimpaction surfaces (Moran, S.M., Pardyjak, E.R., Veranth, J.M., 2013. Understanding the role of grid turbulence in enhancing PM10 deposition: scaling the Stokes number with R_λ . *Physics of Fluids* 25, 115103). Here, we extend this by considering deposition onto realistic vegetative surfaces. Results from wind-tunnel deposition experiments conducted using nonvolatile particles and various types of artificial vegetation under grid-generated isotropic turbulence conditions are presented and compared with the previous idealized experiments. The nonimpaction-surface fraction of the total deposition is shown to scale with the Reynolds number and a new effective area parameterization is developed

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to account for inertial deposition onto nonimpaction surfaces. A combined formulation of the turbulent Stokes number and the effective deposition area are used to collapse the data. The results show that laminar impaction models dramatically under predict deposition for a given classical Stokes number. The new parameterization shows improved performance for deposition onto vegetation with the coefficient of determination (R^2) increasing from 0.15 to 0.65 when accounting for turbulence and nonimpaction-surface deposition area.

Keywords: Stokes number, Deposition fraction, Fugitive dust, Taylor microscale, Fluorometry, Particle deposition

1. Introduction

This [paper](#) describes work done to experimentally investigate the role of turbulence in enhancing particle deposition onto vegetation. The overall goal is to improve the parameterization of PM_{10} (i.e., particulate matter with an aerodynamic diameter less than or equal to $10\ \mu\text{m}$) deposition onto vegetation in atmospheric boundary-layer flows. This was accomplished by extending the previous idealized substrate particulate deposition work of Moran et al. (2013) to realistic vegetative elements.

Understanding the underlying physics of particle transport and deposition is critical to many areas of engineering, biology, and environmental science. Particle transport phenomenon is a complex area of physics involving aspects of fluid dynamics, heat and mass transfer, atmospheric chemistry, and micrometeorology. Many studies have been conducted to better understand the dry deposition processes of particles with length scales spanning many orders

15 of magnitude from nano-scale to millimeter-scale (Wesely and Hicks, 2000).
16 Many factors such as diffusion, surface roughness and adhesion, inertial im-
17 paction, gravitational settling, and re-emission characteristics determine the
18 appropriate modeling approach to use.

19 Depending on particle characteristics (physical size, density, shape, etc),
20 deposition surface characteristics, and atmospheric conditions, an individual
21 solid particle traveling in the wind can either remain suspended or interact
22 with and deposit onto a surface. The primary mechanisms for dry particle
23 deposition are Brownian diffusion, interception, inertial impaction, and sed-
24 imentation (or gravitational settling) (Shao, 2000). Earlier work by Cham-
25 berlain (1967) experimentally determined the deposition velocities of several
26 classes of particles ranging from $0.8\ \mu\text{m}$ to $32\ \mu\text{m}$ onto various surfaces in
27 field and wind-tunnel studies. Further work by Aylor (1975); Slinn (1982)
28 and Aylor and Ferrandino (1985) extended the work to a wider range of
29 particle sizes and surface characteristics.

30 Focusing on inertial impaction physics, May and Clifford (1967) and
31 Marple and Liu (1974) performed detailed laboratory experiments to de-
32 termine the impaction deposition of aerosol particles. These laminar flow
33 results have been subsequently incorporated into atmospheric particle de-
34 position models (e.g., Raupach et al., 2001; Aylor and Flesch, 2001). A
35 brief review of the literature indicates that while these mechanisms have
36 been explained both theoretically and empirically, the specific role of atmo-
37 spheric turbulence on inertial deposition onto vegetative surfaces remains a
38 largely unexplained area (Petroff et al., 2008). Additionally turbophoresis,
39 or particle migration towards walls due to gradients in the turbulence field,

40 is thought to play an important role in deposition (Guha, 2008). Petroff
41 et al. (2009) and Katul et al. (2010) have included turbophoresis parame-
42 terizations derived from pipe flow experiments into one-dimensional inertial
43 impaction deposition models. The results of Katul et al. (2010) indicated,
44 that for particles in the range of 0.1 to 10 μm in vegetative canopies the
45 effect of turbophoresis on deposition was small.

46 Near-source vehicle generated fugitive dust modeling is an area that is
47 especially sensitive to the details of inertial particle deposition parameteri-
48 zations. One way to mitigate roadside dust emissions is to utilize vegetative
49 windbreaks to enhance mixing, reduce flow velocity, and provide deposi-
50 tion surfaces. Several field experiments have demonstrated the impact that
51 roadside windbreaks and vegetative canopies have on reducing fugitive dust
52 (Veranth et al., 2003; Etyemezian et al., 2004; Pardyjak et al., 2008, 2013).
53 These experiments also demonstrate that existing particle deposition param-
54 eterizations significantly under predict deposition (Veranth et al., 2003). In
55 fact, in order to force the existing models to match experimental field data,
56 vegetative elements must be reduced in size by multiple orders of magni-
57 tude (Amatul, 2007; Pardyjak et al., 2013). This mismatch between the
58 experimental and modeled results indicates that typical inertial impaction
59 deposition models do not contain all of the relevant physics and must be
60 improved.

61 Most particle deposition models (e.g., Raupach et al., 2001) parameterize
62 the deposition fraction (DF) as a function of the classical Stokes number
63 (Seinfeld and Pandis, 2012)

$$Stk = \frac{D_p^2 \rho_p C_c u}{18 \mu L_c} \quad (1)$$

64 where D_p is the particle diameter, ρ_p the particle density, C_c the Cunningham
 65 correction factor, u the flow velocity, μ the dynamic viscosity of air, and L_c
 66 is a characteristic length scale of the deposition surface. Physically, for flow
 67 around an object with a characteristic length scale, L_c , the Stokes number
 68 is the ratio of the particle stopping distance to the object's characteristic
 69 length scale. It indicates the ability of a particle to continue moving with
 70 flow streamlines around an object. Interception may occur in cases where a
 71 particle follows a streamline of the flow whose distance from a surface is less
 72 than or equal to the radius of the particle. Inertial impaction or interception
 73 may also occur when the characteristic length scale of the obstacle is small
 74 enough to allow for even low inertia particles to deposit. In the experiments
 75 presented below impaction and interception are indistinguishable, and there-
 76 fore, are combined and referred to collectively as impaction throughout the
 77 manuscript.

78 In turbulent flows, streamlines are highly unsteady leading to situations
 79 where particles may not follow streamlines or where particles experience in-
 80 creased likelihood of interception. Moran et al. (2013) hypothesized that
 81 free-stream turbulence is the missing physical parameter in existing depo-
 82 sition models. They performed a set of wind-tunnel experiments with and
 83 without grid-induced turbulence to isolate the role of turbulence on particle
 84 deposition. Using idealized square polymer substrates with the deposition
 85 faces oriented in all six principle directions, Moran et al. (2013) found that
 86 free-stream turbulence dramatically increases the particle deposition fraction

87 onto surfaces regardless of orientation resulting in substantially higher depo-
88 sition fractions at much lower Stokes numbers than commonly used models
89 (e.g., May and Clifford, 1967).

90 The present work extends the work of Moran et al. (2013) from idealized
91 substrates to realistic vegetative element geometry. The current experiments
92 were designed to further test the hypothesis that particle deposition onto
93 vegetation is enhanced by the presence and intensity of free-stream turbu-
94 lence.

95 2. Experimental Setup

96 2.1. Wind tunnel and turbulence

97 To measure **particle** deposition, a series of wind-tunnel deposition exper-
98 iments were performed with grid-generated isotropic turbulence. The exper-
99 imental methods are based on the procedures of Moran et al. (2013). The
100 experiments comprised three separate components conducted at the same
101 location within the tunnel. Aerosol quantification, turbulence measurement,
102 and the deposition experiments were conducted individually after they were
103 found to be repeatable. The experiments were conducted within the test
104 section of a low-speed wind tunnel of length 2.44 m with a cross section of
105 1.22 m by 0.61 m at operating velocities of 4.9, 8.3, and 9.5 m s⁻¹ (Fig. 1).
106 To generate isotropic turbulence within the wind tunnel, an acrylic grid was
107 placed at the beginning of the test section. The grid was the same 50%
108 solidity grid with 2.54 cm bar thickness used in Moran et al. (2013).

109 The core of these experiments is a mass-balance procedure using a fluores-
110 cent tracer solution with nonvolatile particles injected into the wind-tunnel

111 free stream. The deposition experiments involved measuring vegetation area,
 112 quantifying aerosol size and concentration, measuring the turbulence statis-
 113 tics within the tunnel, rinsing the substrates after deposition, and carefully
 114 quantifying the fluorescence of the diluted wash solution.

Figure 1: Schematic showing the wind-tunnel deposition experiment setup.

115 2.2. Aerosol generation

116 The **particle** deposition experiments consisted of injecting fluorescent
 117 micro-particles into the tunnel free stream in the presence of grid generated

118 turbulence. An Ultra-Sonic Humidifier (USH) (Model V5100NS, Kaz Inc.,
119 Hudson, NY) was used to aerosolize a solution of 80% H_2O , 20% Glycerol
120 ($C_3H_8O_3$). This particular ratio was chosen by Moran et al. (2013) because
121 the resulting particle size distribution was confined to the PM_{10} regime. The
122 solution was mixed with powdered fluorescein sodium salt ($C_{20}H_{10}Na_2O_5$)
123 (Sigma-Aldrich, St. Louis, MO) with a concentration of 0.5 mg mL^{-1} . As
124 the solution was nebulized in the USH, the fluorescein, water, and glycerol
125 mixture was aerosolized into particles with a mean diameter of $\approx 3.2 \text{ }\mu\text{m}$
126 depending on the wind tunnel operating conditions (see Table 2).

127 The exact quantity of water in the aerosol is unknown because the relative
128 humidity was not recorded during the experiments. However, a theoretical
129 discussion of the effect of water within the solution may suffice. In our Stokes
130 number calculations, the density is assumed to be 100% glycerol. The initial
131 solution was 80% water and 20% glycerol and presumably some of the water
132 does evaporate within the wind tunnel. Assuming that no water evaporates,
133 the density of the water-glycerol mixture at room temperature is 1052 kg m^{-3} ,
134 assuming all of the water evaporates, the density is 1260 kg m^{-3} . This
135 provides a range of potential particle density values for the Stokes number
136 calculation shown in Eq. 1. This uncertainty range is shown as **horizontal**
137 bars in the results below.

138 2.3. Model vegetation

139 The deposition experiments tested artificial broad leaf (with three dif-
140 ferent orientations), artificial onion grass, varnished twigs, and **sections of**
141 aluminum welding filler rod. The samples were placed 1.80 m downwind of
142 the turbulence grid and were held in place by a spring clip positioned on a

143 ring stand. The ring stand was positioned such that the samples were lo-
 144 cated at the center line of the wind tunnel. The samples were maintained at
 145 a constant streamwise position by optically aligning the sample with posi-
 146 tion indicator marks placed on the transparent wind-tunnel walls. Spanwise
 147 positioning was likewise visually aligned.

Figure 2: Sample images of the various substrates tested in the deposition experiments. Broad leaf (left) and grass (right) samples shown.

148 Key parameters from the deposition experiments are summarized in Ta-
 149 ble 1. The broad leaf models are silk decorative house plants purchased from
 150 a local craft store (Jo-Ann Fabric and Craft Stores Item 9024050). They are
 151 modeled after Sweetbay Magnolia (*Magnolia virginiana*) with a subtle axial
 152 curve in both axes and smooth surface texture. In Table 1, orientation indi-
 153 cates the angle of the sample with respect to the free-stream wind direction.

154 In addition to being oriented vertically (0°) with the petiole downward and
 155 the adaxial surface facing the wind, the broad leaf was leaned into ($+45^\circ$) and
 156 away from the wind (-45°). The broad leaf was also oriented in an ‘edge-on’
 157 configuration, where the adaxial and abaxial surfaces of the leaves were nor-
 158 mal to the mean wind. The grass samples were likewise purchased from the
 159 local craft store (Jo-Ann Fabric and Craft Stores Item 7854805) and were
 160 modeled after Onion Grass (*Melica bulbosa*) with a smooth polymer fabric
 161 surface finish.

Table 1: Vegetation deposition wind-tunnel experiment summary. A detailed breakdown of Stokes number and other parameters is provided in the Results section. Three tests were performed at each listed speed for each surface.

Substrate	Orientation	# Tests	$(\bar{u})$ (m s^{-1})	Avg Width (mm)
Broad Leaf	0°	9	4.9, 8.3, 9.5	26.2
	-45°	9	4.9, 8.3, 9.5	26.2
	$+45^\circ$	9	4.9, 8.3, 9.5	26.2
	Edge-On	6	4.9, 8.3	28.9
Grass	0°	9	4.9, 8.3, 9.5	1
Metal Rod	0°	18	4.9, 8.3	0.889, 1.575, 2.387

162 Based on preliminary experiments and observations, the experimental
 163 time was varied from 5-30 minutes for different surfaces and tunnel velocities.
 164 The purpose of this large time spread was to prevent any over saturation
 165 or dripping from the leaf, grass sample, or metal rod. For example, the

166 broad leaf experiments needed longer deposition times because of the lower
167 deposition fractions and the higher volume of washing solution needed to
168 wash the leaf. In contrast, the grass experiments needed far less time because
169 the grass has higher deposition fraction and was more prone to saturation
170 and dripping. The real twigs were discovered to exhibit time-dependent
171 fluorescein absorption and the results were discarded. The metal rods of
172 various diameters were used as a twig surrogate to expand the Stokes number
173 range.

174 **3. Measurements**

175 *3.1. Turbulence*

176 Mean and turbulent streamwise velocity measurements were made with
177 a 5.0 μm tungsten hot-wire probe. The hot-wire was operated using an AN
178 1003 Anemometry system (AA Lab Systems Ltd, Israel) sampled at 25 kHz
179 using an NI PCI 6122 DAQ (National Instruments Inc., Austin, TX) with a
180 BNC-2110 connector block (National Instruments Inc., Austin TX) and NI
181 Developer Suite software (Labview Version 10, National Instruments Inc.,
182 Austin TX).

183 The wind-tunnel turbulence intensity was calculated as the ratio between
184 the streamwise-velocity standard deviation (σ_u) and the mean-streamwise
185 velocity ($\bar{u}$). The Taylor microscale (λ) was calculated using the methods
186 described by Bruun (1995), Pope (2000), and Tennekes and Lumley (1972)
187 from the autocorrelation of the fluctuating-streamwise velocity time series.
188 Specifically, a parabola was fit to the first three points of the autocorrelation
189 function and the point where the parabola crossed the ordinate was taken as

the time scale of the Taylor microscale. Taylor’s frozen-flow hypothesis was used to convert this time scale into a physical length scale, λ , by multiplying the time scale by the mean streamwise velocity. Further details on the hot-wire characterization procedure is found in Moran (2012). The results (Table 2) were verified by multiple measurements.

For grid-generated turbulence, the critical parameter that determines the spatial evolution and level of isotropy in the flow field is x/M , where x is the downstream distance from the grid and M is the grid mesh size. According to Pope (2000) and Comte-Bellot and Corrsin (1966), turbulence generated near the grid is non-isotropic with wakes from the individual bars still contributing significantly. Experimental data has shown that for $x/M > 10$, these wakes homogenize and the turbulence becomes approximately isotropic. In the present case, the grid mesh spacing is 8.66 cm and the distance downstream from the grid to the measurement location is 1.8 m resulting in $x/M = 20.8$. The assumption that turbulence is isotropic at the measurement location was further validated by direct comparison of the decay rate of turbulent kinetic (Moran, 2012).

3.2. Aerosol

The particle size distribution was measured using a GRIMM 1.109 laser particle spectrometer (GRIMM Technologies Inc., Douglasville, GA). The GRIMM particle spectrometer utilizes a laser scattering technique to measure particle size distributions (Figure 3). Because the fluorescein salt interferes with the GRIMM laser scattering measurement technique, fluorescein was not included in the water glycerol solution during the aerosol concentration measurement experiments. Deposition experiments were conducted at wind-

Table 2: Measured experimental characteristics. Velocity and turbulence data where obtained using hot-wire anemometry where λ , $\bar{u}$, and σ_u are the Taylor microscale, mean streamwise velocity, and streamwise velocity standard deviation, respectively. Aerosol physical characteristics where measured using a GRIMM 1.109 laser particle spectrometer. D_p is the mean particle diameter ($\pm \sigma$) and C_m is the measured particle concentration ($\pm \sigma$).

$\bar{u}$ (m s ⁻¹)	σ_u (m s ⁻¹)	λ (m)	D_p (μm)	C_m (mg m ⁻³)
4.895	0.2904	0.0093005	3.27 $\pm$ 1.34	0.0069 $\pm$ 7.8e ⁻⁶
8.288	0.4218	0.0107744	3.23 $\pm$ 1.35	0.0060 $\pm$ 4.38e ⁻⁶
9.474	0.4568	0.0104214	3.20 $\pm$ 1.37	0.0053 $\pm$ 4.27e ⁻⁶

215 tunnel operating velocities of 4.9, 8.3, and 9.5 m s⁻¹ and the aerosol **particle**
216 **count** and **the associated** size distribution were measured at each speed. The
217 aerosol **particle count and size distribution over the surface were** represented
218 by a point measurement which was confirmed by measuring the spatial dis-
219 tribution over a 10 $\times$ 10 cm² area surrounding the targeted experimental
220 location (Figure 4).

221 3.3. Fluorescence quantification

222 At the completion of a deposition trial, each sample was placed in a sealed
223 test tube. Samples were then washed with 2.0 – 10.0 mL of distilled water
224 while still in the test tube. The wash volume was varied according to the
225 surface area and experimental time. This rinse was intended to wash off
226 the deposited fluorescein salt from the sample surface and re-suspend the
227 fluorescein. Testing indicated there was very low background fluorescence

Figure 3: The volumetric concentration for the glycerol-water aerosol produced by the USH at three wind-tunnel velocities. Data were acquired at $x = 1.80$ m from the turbulence grid.

on the substrates and no discernible time-dependent fluorescein absorption
besides the wood twigs as mentioned earlier.

After the washing, each test tube was agitated on a vortex mixer for 30
seconds and three $75 \mu\text{L}$ samples from each washing were placed in a well
plate with a pipette. The fluorescence from each test well was measured
using a fluorimeter (1420 Victor3V, PerkinElmer Inc., Waltham, MA). The

Figure 4: Spatial characteristics of the aerosol plume at 1.80 m downstream of the entry to the test section of the wind tunnel. Plots A and B represent no-grid and grid results respectively. Measurements were made at a 5.7 cm spacing; mass concentrations are normalized by the peak concentration.

234 resulting fluorescence intensity was then averaged over three measurements
 235 for each sample.

236 A dilution series was performed with the fluorescein and distilled water
 237 solution to estimate the fluorescein mass from the measured fluorescence in-
 238 tensity (FL). Concentrations ranging from 1×10^{-11} to 0.5 mg mL^{-1} were

239 tested and a linear range from the detectable limit of distilled water fluores-
 240 cence ($\approx 20 \times 10^3$) to the saturation point ($\approx 50 \times 10^6$) was determined. The
 241 concentration of the glycerol-fluorescein mixture (C_w) was estimated from
 242 the following linear fit: $FL = aC_w + b$. Here, $a = 1 \times 10^9$ and $b = -94543$.

243 Using the measured fluorescence intensity from the fluorimeter, the mass
 244 of the deposited glycerol-fluorescein solution (M_w) can be estimated from the
 245 linear regression as

$$M_w = \left(\frac{FL + 94543}{1 \times 10^9} \right) V_w. \quad (2)$$

246 The mass of the fluorescein is a function of the fluorescence intensity
 247 and the volume of the washing solution (V_w) shown in Eq. 2. The overall
 248 deposition fraction can be estimated by dividing the mass of the deposited
 249 particles by the mass of the particles in the airstream.

$$DF(\%) = \frac{Mass\ Deposited}{Mass\ in\ airstream} \times 100\% = \frac{M_w}{\bar{u} A t C_m} \times 100\% \quad (3)$$

250 The mass of the available particles can be thought of as a volume of
 251 particles created by projecting the 2D frontal surface area through the time of
 252 the experiment. Hence, the mass of particles in the air stream is a function of
 253 the mean velocity ($\bar{u}$), frontal area of the sample (A), time of the experiment
 254 (t) and the concentration of the aerosol (C_m) measured with the GRIMM
 255 particle spectrometer.

256 3.4. Area measurements

257 The deposition efficiency is a function of the frontal area of the sample
 258 (Eq. 3). In the case of the broad leaf and grass samples, **digital photographs**

259 and Adobe Photoshop CS5 were used to determine the leaf area. The frontal
 260 area was calculated by identifying the leaf boundaries and comparing pixels
 261 within the leaf relative to an object of known size. The method was found to
 262 be repeatable with an error $\leq 1\%$. Rod frontal area was directly calculated
 263 from the geometry.

264 3.5. Classical Stokes number quantification

265 The classical Stokes number was calculated using Eq. 1. The parameters
 266 for aerosol concentration and particle diameter were measured directly using
 267 the GRIMM 1.109 as described above. The particle density was conserva-
 268 tively assumed to be that of glycerol due to the water evaporation prior to
 269 deposition and the unknown water content as previously discussed. The mass
 270 contribution of the fluorescein salt was not included because of the very small
 271 concentration. The characteristic length scale for the broad leaf was calcu-
 272 lated using the methods of Schuepp (1993) where the characteristic length is
 273 defined in terms of the integrated leaf profile (Eq. 4). The broad leafs were
 274 approximated by a sine-wave fit to the measured major and minor axes of
 275 the leaf, which resulted in an error of $< 2\%$ compared with the pixel based
 276 measured area. The characteristic length for the grass and rod geometry was
 277 simply the element width.

$$L_c = \left[\frac{\int_0^w X(y)dy}{\int_0^w X(y)^{0.5}dy} \right]^2 \quad (4)$$

278 3.6. Turbulent Stokes number

279 The classical Stokes number does not account for the effect of turbulence
280 on the dry deposition of particles. Moran et al. (2013) proposed a new tur-
281 bulent Stokes number (Stk^*) parameterization which combines the classical
282 Stokes number with the Taylor microscale Reynolds number (Re_λ) as follows:

$$Stk^* = Stk Re_\lambda^{0.3}. \quad (5)$$

283 The Taylor microscale Reynolds number used by Moran et al. (2013) is
284 structurally similar to the traditional Reynolds number, however the Tay-
285 lor microscale is used as the characteristic length scale and the fluctuating
286 velocity (σ_u) is used as the velocity scale resulting in

$$Re_\lambda \equiv \frac{\sigma_u \lambda}{\nu}. \quad (6)$$

287 4. Model Development

288 4.1. Modified deposition area parameterization

289 To compare the results of Moran et al. (2013) with the present work,
290 the deposition fraction **definition** was modified with a new scaling to ac-
291 count for the complex geometry of vegetation. Moran et al. (2013) analyzed
292 the impaction surface (the surface with an outward pointing normal paral-
293 lel, but opposite in direction to the mean flow) and nonimpaction surfaces
294 separately and their proposed parameterization was based on the impaction
295 surface only. Nonimpaction-surface deposition was $\approx 10\%$ of the impaction-
296 surface deposition. In addition, the nonimpaction-surface fraction scaled
297 with Reynolds number. Here, a new effective deposition area is calculated

298 using the impaction and nonimpaction-surface data from Moran et al. (2013).
 299 Specifically, the area in Eq. 3 is replaced by an area that is weighted accord-
 300 ing to the nonimpaction-surface deposition contribution published by Moran
 301 et al. (2013) (Table 1). Using this methodology we propose that the area
 302 given in Eq. 3 be written as $A = A_{Frontal} + \gamma(A_{Wetted} - A_{Frontal})$, where
 303 $\gamma = -6.5 \times 10^{-5}Re + 0.43$ represents a nonimpaction-surface weighting fac-
 304 tor scaled by the leaf Reynolds number ($Re = L_c \bar{u} / \nu$), A_{Wetted} is defined as
 305 the total surface area of the object, and $A_{Frontal}$ is defined as the frontal area
 306 of the leaf or cylinder. For the leaf elements, A_{Wetted} is comprised of both
 307 sides of the leaf, while for the cylindrical elements it is the total surface area.
 308 The weighting parameter γ was determined from a best fit of the Moran et al.
 309 (2013) data. The fit is only valid over the range of Reynolds numbers tested
 310 by Moran et al. (2013), which is limited to $400 \leq Re \leq 6000$. Clearly, from
 311 the formulation of γ , at very high Re the weighting factor will actually turn
 312 negative which is not physical.

313 Conceptually, for these complex three-dimension shapes, the deposition
 314 can be described as the superposition of the deposition onto impaction and
 315 nonimpaction-surfaces. Using this conceptual framework, the formulation of
 316 γ is based on the hypothesis that the contribution of nonimpaction-surface
 317 deposition scales with the Re (for our limited range of Re). This effective
 318 area modification was done to: 1) eliminate apparent $DF > 100\%$ due to
 319 the integrated deposition approach of the current experiments, and 2) reflect
 320 real-world deposition fraction onto realistic surfaces accounting for both im-
 321 paction and nonimpaction-surface deposition contributions. In the following
 322 sections, we denote deposition fractions computed using this area weighted

323 scaling as DF_{total} .

324 5. Results

325 The results from the wind-tunnel experiments illustrate increased **parti-**
326 **cle** deposition compared to previous laminar results. The deposition experi-
327 ments span a range of classical Stokes numbers from ≈ 0.005 to 0.3 (Fig. 5).
328 Generally, the broad leaf experiments are on the very low end of the experi-
329 mental Stokes number range due to the relatively large characteristic length
330 scale. The DF_{total} for the broad leaf experiments appears to be relatively
331 independent of Stk . This is due to the very small Stk and **the trends agree**
332 **with previous work (Marple and Liu, 1974)**. Broad leaf angle relative to the
333 wind ($\pm 45^\circ$) has no observable effect on the deposition fraction. The data
334 from Moran et al. (2013) are also shown in Fig. 5. The figure indicates that
335 the more two-dimensional broad leaf and edge-leaf deposition experiments in
336 this work have similar enhanced deposition as the idealized substrates used
337 in Moran et al. (2013). The grass and rod experiments have much smaller
338 characteristic lengths and are in the higher Stokes number range with some
339 samples even crossing the fit of Marple and Liu (1974). This different behav-
340 ior warrants explanation. For elements with Stk to the left of the Marple and
341 Liu (1974) vertical line, deposition appears enhanced (similar to the Moran
342 results), while elements to the right seem to have reduced deposition. The
343 laminar Marple and Liu (1974) results only include the deposition face and
344 omit nondeposition-face processes, which are much less efficient. Hence, at
345 higher Stk , our Re -based scaling reflects the fact that the non-impaction
346 deposition increases at a rate much slower than on impaction surfaces.

347 In an effort to improve the scaling shown in Fig. 5 and produce a useful
 348 parameterization, the modified deposition results have been scaled by the
 349 turbulent Stokes number, Stk^* . A nonlinear least squares regression was used
 350 to compute a functional relationship between the modified deposition fraction
 351 and Stk^* . A combined dataset, which included the results from Moran et al.
 352 (2013) and the vegetation results from this work, was created and the general
 353 functional form of Moran et al. (2013) was used but with newly calculated fit
 354 coefficients. The results of the combined regression are shown in Eq. 7 and
 355 plotted in Fig. 6. When compared to the fit of idealized surfaces in Moran
 356 et al. (2013), the present fit has more scatter. We hypothesize that this is due
 357 to the inclusion of more complex deposition processes onto realistic surfaces.
 358 Physically, the lower exponent on the Stk^* term indicates that the turbulent
 359 Stokes number contribution to the total deposition is attenuated somewhat
 360 when considering all deposition surfaces. The fit clearly shows improvement
 361 compared to the Marple and Liu (1974) laminar theory and the Moran et al.
 362 (2013) fit (Table 3).

$$DF_{total} = 100 - \frac{100}{2.049(Stk^*)^{1.19} + 1} \quad (7)$$

363 To illustrate the impact of the different parameterizations on estimated
 364 deposition fractions, consider a 5.0 mm wide grass element subjected to a
 365 flow with a 3.8 m s^{-1} wind speed and suspended $8.0 \text{ }\mu\text{m}$ sand particles. The
 366 resulting **classical** Stokes number is 0.2, the Reynolds number is 1×10^3 and
 367 the laminar theory deposition curve indicates a deposition fraction of around
 368 25%. Assuming similar turbulence intensity (6%) and λ (9.3×10^{-3}) as in
 369 the present work, $Re_\lambda = 110$ and $Stk^* = 0.85$ and the DF_{total} is 65%.

Table 3: Model fit comparison between Marple & Liu (1974) laminar data, Moran et. al (2013) idealized substrates, and the present work. r^2 is evaluated for the combined dataset of Moran et. al (2013) and the present work.

Fit	Eqn	r^2
Marple & Liu (1974)	-	0.15
Moran et. al (2013)	$DF = 100 - \frac{100}{440.5(Stk^*)^{3.88}+1}$	0.42
Present Work	$DF_{total} = 100 - \frac{100}{2.049(Stk^*)^{1.19}+1}$	0.65

370 The results from our vegetation deposition experiments generally support
371 the findings of Moran et al. (2013); however, some of the findings deserve
372 more detailed discussion. The parameterizations for turbulence enhanced
373 particle deposition are incomplete when accounting for off-axis deposition.
374 The data from Moran et al. (2013) show some Reynolds number dependency
375 in the off-axis fraction of total deposition where increasing Re results in
376 decreased off-axis proportional deposition. This relationship was used to
377 calculate the **proposed** weighting scaling to effectively increase the area used
378 in the deposition fraction calculations while maintaining the physics of the
379 Stokes number. The overall effect of this area parameterization is to include
380 *total* deposition onto a vegetative element and not to partition the deposition
381 by surface.

382 The broad leaf results in the $Stk^* \approx 0.015$ regime show very low de-
383 position fraction as anticipated for the small Stokes number. However, the
384 edge-on experiments exhibited increased deposition indicating turbulence is
385 enhancing the deposition onto off-axis faces of the leaf surface. This is also in

386 agreement with Moran et al. (2013), however, the current parameterization
 387 does not take into account the element orientation as no effect was observed
 388 in the present deposition data. The characteristic length scale in the Stokes
 389 number calculation was the same for both the broad face and edge-on orien-
 390 tation. In addition to leaf orientation, the effect of leaf bending or fluttering
 391 was not directly considered in the analysis or the parameterization. The-
 392 oretically, the fluttering and twisting of a leaf would instantaneously alter
 393 the local Stokes number by changing the apparent flow velocity as the leaf
 394 fluctuates between advancing into and retreating from the wind. Twisting
 395 of the leaf may also have effects on the characteristic length scale. Much
 396 work remains to perform the necessary experiments to fully understand the
 397 impact of these motions.

398 The results clearly indicate that deposition models may be improved by
 399 including turbulent physics. The present work and the work of Moran et al.
 400 (2013) were based on wind-tunnel data, which introduces unavoidable scal-
 401 ing limitations. The turbulence intensity found in real vegetative canopies is
 402 much higher than what can be produced in the wind tunnel. Further work
 403 with a wider range of turbulence intensities and vegetative element designs
 404 could provide insights into the mechanisms and scaling of inertial impaction.
 405 Practical limitations of field experiments and wind-tunnel scaling suggest
 406 the need for direct numerical simulations (DNS) or other detailed simulation
 407 work to establish better bounds on the physical parameters. Lagrangian par-
 408 ticle modeling driven with DNS or large-eddy simulations similar to Soldati
 409 and Marchioli (2009) could be used to establish these improved models. Fur-
 410 ther work on the specific scaling of the Reynolds number dependence on the

411 off-axis fraction of total deposition needs to be done over a broader range of
412 Reynolds numbers and for vegetation geometries. Furthermore, one of the
413 main aspects of aerosol deposition that remains unexplored is the effect of
414 sheltering and wake interference within a canopy. The relative spacing be-
415 tween the individual vegetative elements is hypothesized to be a significant
416 factor in real world deposition physics.

417 The proposed parameterization for inertial impaction and deposition of
418 PM_{10} sized aerosol particles includes turbulence parameters and methods for
419 accounting for nonimpaction-surface deposition on the entire surface. These
420 enhancements are beneficial for application of this parameterization to real-
421 world situations with arbitrary element geometry and turbulence enhance-
422 ment on all surfaces. The combination of frontal projected area and wetted
423 area into an effective deposition area to account for nonimpaction-surface
424 deposition also represents an important improvement towards application to
425 real world vegetative canopy elements.

426 **6. Acknowledgements**

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Figure 5: Total deposition fraction (DF_{total}), computed using the proposed weighted area method described in the text, as a function of classical Stokes number for various vegetative elements. Results from Marple and Liu (1974) and Moran (2013) are shown for comparison. Horizontal error bars indicate uncertainty in aerosol particle density and vertical error bars represent one standard deviation for averaged experiments. Only one representative broad leaf horizontal error bar is shown for clarity. Results illustrate significantly higher deposition at lower Stokes number similar to the findings of Moran (2013).

Figure 6: Total deposition fraction (DF_{total}) as a function of modified Stokes number as defined in Moran et al. (2013). Horizontal error bars indicate uncertainty in aerosol particle density and vertical error bars represent one standard deviation for averaged experiments. Only one representative broad leaf horizontal error bar is shown for clarity. The dotted line is a least-squares best fit to all of the data.

Table 4: Data from the wind-tunnel deposition experiments on model broad leaves, grass, and metal rods. Data is provided for all averaged wind-tunnel velocities ($\bar{u}$) and distances downstream of the turbulence grid (x). The turbulence and particle characteristics can be found in Table 2. The standard deviation of the DF_{total} ($DF_{total}Std$) is given for averaged experiments only.

Surface	$\bar{u}$ (m s ⁻¹)	DF_{total}	$DF_{total}Std$	Stk	Stk^*	x (m)
0° Broad Leaf	4.895	2.43%	-	0.0081	0.0363	0.0207
	4.895	1.61%	-	0.0058	0.0260	0.0289
	4.895	1.62%	-	0.0058	0.0260	0.0289
	8.288	2.83%	-	0.0133	0.0701	0.0207
	8.288	2.52%	-	0.0095	0.0502	0.0289
	8.288	3.19%	-	0.0095	0.0502	0.0289
	9.474	3.42%	-	0.0149	0.0794	0.0207
	9.474	3.24%	-	0.0107	0.0569	0.0289
	9.474	3.55%	-	0.0107	0.0569	0.0289
+45° Broad Leaf	4.895	2.46%	-	0.0081	0.0363	0.0207
	4.895	1.81%	-	0.0058	0.0260	0.0289
	4.895	2.52%	-	0.0058	0.0260	0.0289
	8.288	2.86%	-	0.0134	0.0700	0.0207
	8.288	2.93%	-	0.0096	0.0502	0.0289
	8.288	2.97%	-	0.0096	0.0502	0.0289
	9.474	4.64%	-	0.0150	0.0794	0.0207
Continued on next page						

Table 4 – continued from previous page

Surface	$\bar{u}$ (m s ⁻¹)	DF_{total}	$DF_{total}Std$	Stk	Stk*	x (m)
	9.474	3.36%	-	0.0107	0.0569	0.0289
	9.474	3.63%	-	0.0107	0.0569	0.0289
	4.895	3.46%	-	0.0081	0.0363	0.0207
	4.895	4.72%	-	0.0058	0.0260	0.0289
	4.895	3.70%	-	0.0053	0.0239	0.0314
-45° Broad Leaf	8.288	4.39%	-	0.0134	0.0700	0.0207
	8.288	3.60%	-	0.0096	0.0502	0.0289
	8.288	3.60%	-	0.0096	0.0502	0.0289
	9.474	5.58%	-	0.0150	0.0794	0.0207
	9.474	4.57%	-	0.0107	0.0569	0.0289
	9.474	4.15%	-	0.0107	0.0569	0.0289
	4.895	9.58%	0.42%	0.0058	0.0260	0.0289
	8.288	8.77%	1.21%	0.0096	0.0502	0.0289
	8.288	8.77%	1.21%	0.0096	0.0502	0.0289
Grass	4.895	68.85%	2.17%	0.1676	0.7506	0.0010
3 samples ea speed	8.288	83.69%	12.28%	0.2770	1.4500	0.0010
	9.474	46.69%	0.68%	0.3098	1.6443	0.0010
0.889mm rod	4.895	76.41%	4.69%	0.1840	0.7354	0.0009
3 samples ea speed	8.288	78.36%	29.95%	0.3116	1.6310	0.0009
1.575mm rod	4.895	62.50%	14.97%	0.1039	0.4151	0.0016
3 samples ea speed	8.288	46.70%	25.82%	0.1759	0.9207	0.0016
2.387mm rod	4.895	18.32%	0.48%	0.0685	0.2738	0.0024
3 samples ea speed	8.288	35.31%	1.66%	0.1160	0.6073	0.0024

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