

CONIFER PM_{2.5} DEPOSITION AND RE-SUSPENSION
IN WIND AND RAIN EVENTS

A Thesis

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ABSTRACT

Recent EPA rulings allow State Implementation Plans (SIP) to include new urban tree plantings as a measure of air pollution abatement, creating an urgent need for accurate estimates of pollution removal by trees. Deposition velocities (V_d) of particulates to trees have been reported for a number of species without explicitly recognizing that observed deposition is a net process, the sum of particle deposition and re-suspension. This has implications for atmospheric models that include a separate re-suspension term to estimate PM loading to trees. Wind tunnel tests at 5 m/s wind speed report 2.5% resuspension with a conifer species over a half day (Ould-Dada). However, in the native environment higher wind speeds are suspected to be responsible for the majority of resuspension of $PM_{2.5}$. In the present study, three conifer species were dosed with KNO_3 D_p 2.5 μm particulates and exposed in a wind tunnel to winds of 6.5, 10, and 13 m/s for 5, 10, or 20 minutes, to determine $PM_{2.5}$ resuspension rates. Deposition velocities were also determined over a range of PM concentrations. Though the removal of particles from the air is small, re-suspension from *Pinus strobus* increased from 0% at 6.5 m/s to 20% of the original dose removed at 10 m/s and 50% of the original dose removed at 13 m/s. *Taxus cuspidata* had low rates of resuspension (20% of the original dose) at all three wind speeds, while *Tsuga canadensis* had no resuspension. V_d are 0.02 cm/s for *Tsuga*, 0.01 cm/s for *Pinus*, and 0.005 for *Taxus*. Deposition velocity was found to be related to complexity of needle and branch arrangement, and not of total needle surface area as hypothesized. Re-suspension is likely to result from mechanical jarring of needles at high wind speeds rather than direct scouring by the wind. An analysis of wind conditions in upstate New York revealed that wind events of a magnitude sufficient to cause resuspension in *Pinus* occur 1.25% of the time in January and 0.07% of the time in July. The implications of these findings are: models of pollution removal by urban trees (ie, The

Urban Forest Effects Model, UFORE) underestimate the amount of PM_{2.5} retained by leaves by 50%.

BIOGRAPHICAL SKETCH

Marcie Pullman has dedicated her career to understanding and elucidating factors affecting human quality of life. Marcie grew up in the sunshine and redwoods of Northern California, and adopted the natural world as part of her everyday lifestyle, enjoying the benefits of clean air and clean water amidst a fast-growing region of the world. After earning a B.A. in Biology from Swarthmore College in 1996, she returned to the San Francisco Bay Area to investigate the benefits of traditional methods of healing and lifestyle, like yoga, massage, and acupuncture, with a hospital research team. She then began her own professional massage practice, in which she as a practitioner of massage learned the benefits of direct hands on touch. She maintained a massage practice for three years while she gathered a clientele base of amateur and professional athletes and those attempting to become athletes. During this time, traveling to five continents to remote villages and megacities, Marcie grew to become aware of the environmental hazards that residents of other parts of the world face as a daily challenge to their own health. Marcie came to the Horticulture Department at Cornell University in the Spring of 2007 to work with Dr. Thomas H. Whitlow on this Masters thesis on air quality and the benefits that trees provide. She is the daughter of an environmental health engineer and an environmental health regulator, and decided to join in the family pursuit for environmental health.

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BACKGROUND

The migration of people into urban centers and the parallel rise of industry within these centers has brought more people into contact with air pollution than ever before (Andreae, 1995). Exposure to air pollution is a quality-of-life issue; the human body is vulnerable to foreign matter in the air and respiration brings air pollution into contact with the respiratory tract. Air pollution in high concentrations can cause immediate physical symptoms like rapid pulse and restricted breathing, but at every level of concentration and even trace amounts, it is considered deleterious to health (Levy et al., 2000). Clean air is being turned into a commodity that cities now advertise, through citing research that suggests moving to a city with cleaner air improves lung function (Avol et al., 2001; Bayer-Oglesby et al., 2005; Downs et al., 2007).

Trees have gained recognition for their contribution to cleaning the air, because they input oxygen into the air and remove pollution. This classic belief about the protective status of trees warrants strict scientific inquiry to quantify benefits to air quality. This thesis will report on the ability to remove pollution from the air for three species of conifer. I will focus on PM_{2.5}, airborne particles with an aerodynamic diameter of 2.5 μm or smaller, because of the thousands of trace chemical pollutants in the air we breathe, public health research has determined PM_{2.5} to be the closest correlated to morbidity and mortality (Vedal, 1997). First, I will discuss the origin and composition of PM_{2.5}, why it is a significant threat to health, and then discuss how trees interact with this pollutant and finally introduce the present study that contributes to our understanding of the air quality benefit trees provide.

The Origin of Particulate Matter

PM_{2.5} is the name given to airborne particles having an aerodynamic diameter of 2.5 μm or smaller. This size class has a residence time in the air of minutes to days, tending to remain in the air because of the small particle size. PM_{2.5} is comprised of particles from many different origins, yet anthropogenic activities are the dominant source of PM_{2.5} in the urban atmosphere (Pandis et al., 1995). A lesser source of PM_{2.5} is salt, sand, and crustal elements of the earth stirred up from the wind and natural inputs like volcanism and forest fires.

The origins of PM_{2.5} are in primary emissions such as elemental carbon and organic carbon, and also in secondary aerosols formed in the atmosphere via gas-to-particle transformations (Pandis et al., 1995). These transformations involve primary pollutants like nitric oxide (NO), emitted from vehicles, and sulfur dioxide (SO₂) emitted by coal-burning power plants, which are chemically transformed in the atmosphere into secondary pollutants like HNO₃ and H₂SO₄, compounds with a more oxidized arrangement and correspondingly a more antagonistic effect on the human body (Davies, 1995). Gas-to-particle transformations occur by condensation when compounds like HNO₃(g) and H₂SO₄(g), diffuse onto particle surfaces, and remain attached.

At the city scale, the atmosphere has a constant input of gaseous emissions that joins ambient pollutants to undergo general oxidizing reactions. Vehicle emissions also introduce particles into the air, uncombusted hydrocarbons that fit into the PM_{2.5} category. Gas and particles interact heterogeneously and homogeneously, with the

general effect that particles grow in size. A collision by a gaseous molecule onto a particle is called condensation.

A second category of collision happens in which homogenous gaseous molecules nucleate on themselves, growing particles out of high concentrations of gas (Seinfeld and Pandis, 1998). This is the pathway that many sulfuric species take to grow into particles, as sulfuric species have been found to nucleate without seed particles present (Zhang and Wexler, 2002; Zhang et al., 2004). The third category of collision is particle-particle, remaining together in a process called coagulation (Pandis et al., 1995). Once larger than 70 nm, a particle will continue to grow in size because it occupies enough physical space that molecules will constantly collide with it (Seinfeld and Pandis, 1998). There is a natural ceiling effect, in which particles that grow larger than 1-2.5 μm are pulled down to Earth by gravity and inertial settling, in which the inertia of a particle traveling in an air stream that curves around a leaf forces it to fall out of the air flow and onto the surface of the leaf. Very few natural processes remove particles 1 μm or smaller, other than rain, snow, and dry deposition, which is the natural settling of particles onto surfaces outlined above. As $\text{PM}_{2.5}$ amasses in the atmosphere it increases our exposure to fine particulate matter which compromises human health.

All three categories of collisions increase the size of particles in the air, and with the daily inputs of emissions into the air, the urban atmosphere can contain a great deal of $\text{PM}_{2.5}$. American cities have a trend of improved $\text{PM}_{2.5}$ by annual average, with a 44 percent average decline in $\mu\text{g}/\text{m}^3$ between the 1980's and 2006 (Schwartz and Hayward, 2007) and a range of averages by state from 4 $\mu\text{g}/\text{m}^3$ in Hawaii to 14 $\mu\text{g}/\text{m}^3$ in California (Environmental Protection Agency, 2003). However, new air quality standards will begin to be enforced in 2010, bringing the acceptable annual

average from $65 \mu\text{g}/\text{m}^3$ to $35 \mu\text{g}/\text{m}^3$, and an anticipated 29 states will have at least one monitoring site violating the standard (Schwartz and Hayward, 2007).

Biomedical effect of PM_{2.5}

Particulate matter poses a direct threat to human health when it is breathed into the respiratory tract. Particles larger than $2.5 \mu\text{m}$ generally deposit in the upper respiratory tract (Thurston et al., 1994), but particles $2.5 \mu\text{m}$ and smaller travel deep into the lungs and embed into fragile alveolar tissue where gas exchange takes place, decreasing the surface area for exchange in addition to landing foreign and possibly toxic particles in the body (Liu and Huza, 1995). This restricts the functioning of the lung, inhibiting full respiration and forcing the heart to pump faster to circulate the required amount of oxygen, a long-term strain on the cardiovascular system (Lippmann, 2003). In this deepest region of the lungs, debris is removed by absorption into blood vessels or by immune cells that bring the particle into the circulatory system, bringing oxidizing agents like SO_4 into the body. PM deposition into the lung can instigate an immediate and wide-ranging cascade of negative health effects on the subject, including inflammatory and immunogenic responses in the lung tissue, autonomic nervous system effects causing airway restriction, cardiac dysrhythmias and reduced blood flow to muscle tissue (Rundell et al., 2007). In children, exposure to $\text{PM}_{2.5}$ can cause slower growth of lung function and asthma (Lippmann, 2003). In the elderly, exposure to $\text{PM}_{2.5}$ can cause death from heart failure (Lippmann, 2003). Over time repeated stresses on the adult body become diseases like asthma, bronchitis, cardiovascular disease, and lung cancer, which epidemiological studies find clearly related to exposure to $\text{PM}_{2.5}$ (Laden et al., 2000; Namdeo and Bell, 2005; Wellenius et al., 2006). The primary pollutants which accumulate to form $\text{PM}_{2.5}$ compromise human health as well (Carlisle and Sharp, 2001), therefore it is likely that large particulates

made of the same toxic chemicals are also hazardous in their own right. PM_{2.5} is also suspected of being a burden to health based solely on its size properties and the way it interacts with the respiratory system (Lippmann, 2003).

Regulating the Public Health Problem PM_{2.5}

Today, PM_{2.5} leads air pollutants in all-time cause of death (Levy, 2005). Particulate matter has been found to be deleterious to health at any level because morbidity-mortality relationships are linear to the lowest observed concentration (Schwartz and Zanobetti, 2000). A recent meta-analysis of research relating urban air pollutants to resident health summarizes twenty years of research covering 29 cities worldwide with these relationships: for every 10 µg/m³ increase in PM₁₀ there is a 7% increase in daily mortality citywide, with greater effects where the ratio of PM_{2.5}/PM₁₀ is highest (Levy et al., 2000).

A set of standards called the National Ambient Air Quality Standards (NAAQS) regulates PM_{2.5} daily and annual concentrations because of mounting evidence that acute doses as well as chronic exposure are harmful (Villeneuve et al., 2002). The first standards for total suspended particulates in the United States were established with the Clean Air Act in 1970, however, standards for PM_{2.5} were not established until 1997, when the differentiation between the effects of PM₁₀ and the much more serious effects of PM_{2.5} became clear (Vedal, 1997). Today's NAAQS standard for PM_{2.5} is 35 µg m⁻³ daily average and 15 µg m⁻³ annually. The EPA mandated stricter standards in 2005 that go into effect in 2010, and in doing so an estimated 85% of Americans were suddenly living in a city that did not meet the standards (Johnson and Graham, 2005). Metropolitan cities in 21 states in U.S. are not attaining these regulations currently. States with non-attainment areas are required

to write and implement a plan to bring local air quality up to standard, or their state highway funding, representing millions of dollars, can be withheld.

Reducing emissions at the source, for example restricting car access to downtown locations, or relocating industry away from residential settings, is the most direct method to reduce PM_{2.5}. State implementation plans, as of 2004, can now officially incorporate new tree plantings into their pollution removal plan as voluntary measure (Environmental Protection Agency, 2004), although the EPA suggests the length of time required for benefits to emerge from planting new trees makes tree plantings more suited for maintaining air quality standards than attaining them. This new allowance makes it very important to quantify the interaction between PM_{2.5} and trees, in order to provide an accurate estimate of the contribution to air quality that trees provide.

Interaction Between Trees, Air Mass, and Particles

PM_{2.5} eventually settles onto surfaces of all kinds through a process called dry deposition. Of the available surfaces on Earth, trees capture a higher proportion of particulate than other types of vegetation because they allow the wind to move through them while the high surface area of leaves allows particles to fall out of the air and deposit. Field research following the Chernobyl accident has confirmed 20% more PM_{2.5} deposition in forests than in adjacent grasslands (Bunzl et al., 1989). Modeling PM_{2.5} deposition regionally has incorporated total surface area of a vegetation into the estimation of pollution removal (McPherson, 1994; Nowak et al., 2003). As air flows and moves across leaves, windspeed slows in proximity to the leaf, and just above the leaf is a quiet layer of air called the boundary layer. Particles move towards the surface through turbulent transfer, and then diffuse through the boundary layer (Lovett, 1994; Pandis et al., 1995). Particles diffuse at

rates inversely proportional to their radius according to the Einstein- Stokes Law, which predicts that smaller particles will diffuse towards the leaf the fastest.

Diffusion is also proportional to the number of particles present, according to Ficks Law. Smaller particles are in greater abundance because the origins of particles are in gas-to-particle transformations, so this predicts more smaller particles will diffuse.

A particle riding through the air can be dropped by inertia as air flow moves around leaves and impacts onto the leaf (Gregory, 1973). Contact can lead to an immediate bounce off back into the airstream, which has been estimated to occur 15% to 70% of the time based on location of sampling stations in tree canopy and wind speed (Wu et al., 1992). Contact also leads to deposition, in which the particle comes to rest on the surface.

The particle will remain on the leaf for an interval of time before an event causes it to detach and re-suspend back into the airstream. Apart from the particle being out of direct air flow, there are forces that will encourage particles to remain on the leaf. These forces include electrostatics, in which particles containing water experience a polarization of charge that holds the particle to the surface. Electrically charged air has been found to encourage deposition in particles < 200 nm at wind speed < 1 m s⁻¹, (Tammet et al., 2001) presumably based on lower bounce off frequency.

Adhesive forces on the leaf surface can occur if the leaf is transpiring and water molecules interact with the particle.

Deposition velocity (V_d) is an expression used to compare particle capture of various surfaces including tree species. Deposition velocity is defined as the slope of particle flux to the surface ($\mu\text{g cm}^{-2} \text{s}^{-1}$) versus the average particle concentration

in the air ($\mu\text{g cm}^{-3}$). Deposition velocity, (cm s^{-1}) has been calculated in the field on urban trees, woodland trees, and experimentally in the wind tunnel with branches and whole potted trees. It has been found in woodland trees and confirmed in wind tunnel studies that the total surface area of needles or leaves on a length of branch is a defining characteristic of V_d (Beckett et al., 2000a; Beckett et al., 2000b). Pine needles are highly dissected and have a high surface area morphology compared to flat broadleaves, per length of primary branch, and have been found to have V_d ten times higher than broadleaves (Beckett et al., 2000b). In addition to one-dimensional surface area of leaves, elements of microstructure have additive surface area, like stomata and pubescence, both of which have been found to increase particle uptake in wind tunnel experiments (Burkhardt et al., 1995; Chamberlain and Chadwick, 1972). Microstructure is not conventionally included in surface area measurements of needles or leaves, and has been studied to further determine characteristics that influence V_d . Pine needles can exude a hydrophobic waxy cuticle, a smooth covering over the needle that allows for very little microstructure surface area. The surface area of trees is also characterized by Leaf Area Index (LAI), the square meters of leaf surface area per square meter of ground. Higher LAI indicates more surface area relative to the ground, but has not been found to increase V_d significantly (Biel, 2007). In this study, deposition velocity is measured on 25 cm length branches. These V_d can not be applied to whole trees because they differ in LAI, and the characteristic dimensions in space. Generally, V_d is expected to increase for trees that have more dissected leaves, more surface area of leaf per length of branch and per square area of ground.

Particle deposition research has employed the use of wind tunnels for a half century to observe particle behavior closely. However, it must be noted that air flow conditions in the wind tunnel contain an artifact of the design. In the natural setting,

turbulence exists within the air mass structure. This is a large scale turbulence, that begins as wind picks up speed over rough surfaces and results in temporary wind speed maxima as vortices move through space. The wind tunnel does not have the size for large and complex turbulence structures to develop that are in part responsible for fluctuation in windspeed; instead windspeed conditions are more consistent with smaller turbulent structures.

The Reynolds number describes the relative flow of fluid around objects across a range from laminar to turbulent (Reynolds, 1883). There are several Reynolds numbers relevant to wind tunnel-vegetation studies, which relate the size of the object in flow to the speed of the fluid (equation 1). Authors have reported the Reynolds number for the wind tunnel itself (Beil 2007), although this number describes the conditions created for the experimental model. A second Reynolds number exists that describes the flow around individual needles, without considering the degree of turbulence in air flow before it hits the needle. This local Reynolds number for the needle is contained within a third Reynolds number that considers the transverse cross-section of the whole branch as the length of air flows over.

$$\frac{\rho v_s L}{\mu}$$

Equation 1. Reynolds Number, $R_e = \frac{\rho v_s L}{\mu}$

ρ is the density of air (kg m^{-3}), v_s is the fluid velocity (m s^{-1}), L is the characteristic length (m), μ is kinematic viscosity ($\text{kg m}^{-1} \text{s}^{-1}$).

The transverse sections of the three species are compared in two views, the sagittal plane and the coronal plane, to illustrate the difference in structural design between the species (Figure 1). On the sagittal plane, all three species have the same approximate width, and a 90° rotation to the coronal plane reveals differences in

species design. Pine has needle fascicles attaching to the primary branch in 360°, where yew and hemlock have secondary branches that branch out on the sagittal plane only.

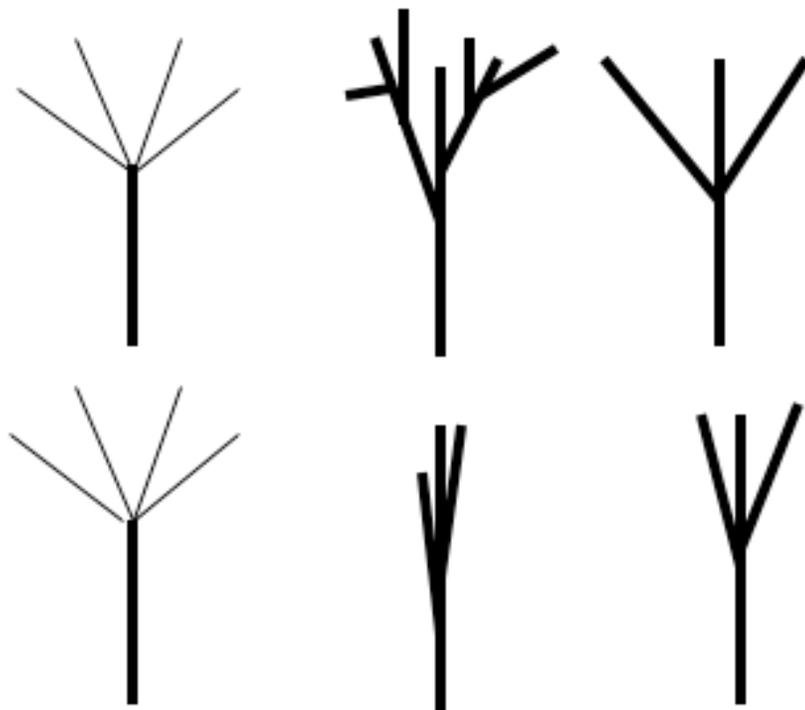


Figure 1. Pine, Hemlock, Yew, transverse sections. Bottom row is rotated 90° to illustrate the difference in structural design between species.

Transverse section lengths for branch samples that are 25 cm long are 0.7 m for pine, 0.4 m for yew, and 0.2 m for hemlock. Reynolds numbers for the thinnest transverse section, the coronal plane, are presented below (Table 1). The rationale for selecting this perspective on the branch is related to air flow. Air flow approaching a tree will impact one branch at a time while moving all the way through it. The specimens have the same basic width on the sagittal plane, but air will flow much further to get through the coronal plane for pine. This characteristic length is interacting with the air flow and examined to determine the differences in turbulence-generating morphology between the species.

Table 1. R_e for needle and thinnest transverse of specimen.

wind speed ($m\ s^{-1}$)	species	needle characteristic dimension (m)	R_e	transverse cross-section (m)	R_e
1.2	pine	0.0003	24	0.07	5600
	yew	0.0020	160	0.04	3200
	hemlock	0.0010	80	0.02	1600
6.6	pine	0.0003	132	0.07	30800
	yew	0.0020	880	0.04	17600
	hemlock	0.0010	440	0.02	8800
9.9	pine	0.0003	198	0.07	46200
	yew	0.0020	1320	0.04	26400
	hemlock	0.0010	660	0.02	13200
12.9	pine	0.0003	258	0.07	60200
	yew	0.0020	1720	0.04	34400
	hemlock	0.0010	860	0.02	17200

The Reynolds numbers reveal that air flow around individual needles for all three species is laminar, with the quietest flow around pine. When the cross-section of the branch is considered, pine has the largest characteristic length, therefore it has the most turbulent flow at this scale, while yew and hemlock have smaller scale turbulence. While the local R_e number is certain, R_e implies a solidity of structure that trees do not have at larger scales; needles are solid and air flow is forced to go around, while the widest transverse section does not act like a solid in fluid air because air will flow around each needle and branch, although the majority of the flow goes around the branch entirely. R_e for the widest transverse aspect is included side-by-side with local R_e to illustrate the impact of considering scale on turbulence, while the amount of turbulence will also be affected by the number of total needles because air flow will move around each needle separately. The working section of

the wind tunnel has a Re number of 32,000, indicating completely turbulent flow. Particles in this air flow are moving within this turbulence, which conveys particles to the top of the boundary layer while at the same time reducing boundary layer thickness.

Resuspension

Resuspension is closely tied to the speed of the wind. In wind tunnel trials a difference of four orders of magnitude is found with rye grass and $2\ \mu\text{m}$ particle resuspension flux at windspeeds of $3\ \text{m s}^{-1}$ and $18.5\ \text{m s}^{-1}$ (Gillette et al., 2004). The mechanisms responsible for resuspension of particles back into the air are three: (i) viscous, when the force of air flow is great enough to detach the particle, or (ii) turbulent, in which energized turbulent air disrupts the boundary layer and lifts particles away into the airflow, or (iii) detachment from vibration or shaking of the whole leaf (Gillette et al., 2004). The most active component of resuspension for particles $< 2\ \mu\text{m}$ has been found to be (iii) the physical movement of the leaf. In order to determine this, Gillette painted the tips of rye grass with assorted size particles, and measured the kinetic energy in the individual blade as it oscillated in the wind while recording the resuspension of different size classes. All coarse size particles resuspended through aerodynamic force alone, the drag force from wind being strong enough to remove them. For fine particles, the force created from the wind was not primarily responsible for resuspension, instead mechanical jarring and slapping of surfaces together produced 85% of resuspension. This finding highlights the specific actions of particles based on size. It also establishes a context for the original resuspension study on oak and pine with particles with diameters 85-175 μm (Gillette et al., 2004). These larger particles were confirmed to act entirely differently in wind, and had resuspension patterns that do not reflect $\text{PM}_{2.5}$. It is expected in the present study, resuspension will be highest in species that react to

wind by quick or sudden movement of leaves. R_e calculated for these species indicate that at the scale of the full specimen cross-section, turbulence will be greatest in pine, next yew, and least in hemlock. This turbulence could cause the branches themselves to move, or simply disrupt the boundary layer on the leaf. If this turbulence is great enough, branch or needle movement will begin to move and mechanical resuspension could occur. If mechanical forces do not occur during the wind trials, aerodynamic forces will bring about a smaller degree of resuspension, seen most in pine, then yew, and least in hemlock.

An estimate of total resuspension for trees is important in calculating the total amount of $PM_{2.5}$ removed by the urban canopy. A hallmark study for the benefits of trees on urban air quality, Air Pollution Removal by Chicago's Urban Forest (McPherson, 1994), uses an estimate of 50% total resuspension based on early study. This original estimate has since been incorporated into the Forest Service's UFORE (Urban Forest Estimate) model, which provides an often used model to cities for estimating the particulate removal worth of their urban canopy. This estimate means that tree pollution removal and retention is only half of what V_d predicts it is, because the other half is resuspended into the atmosphere. The 50% estimate is based on very large particles (88-175 μm) in a breeze 3-5 $m s^{-1}$, with the finding that after one hour, 90% of the particles on oak were resuspended, while 10% were resuspended from pine (Witherspoon and Taylor, 1969). Particles this large will experience a large drag force from wind, and consequently are expected to be pulled off of a leaf much easier and resuspend.

A more recent study addressing resuspension was designed to test the national safety issue radioactive nuclear fallout, utilized particles 1.85 μm at 5.5 $m s^{-1}$ in the wind tunnel, to estimate the fraction of fallout that resuspends. In this study, Ould-

Dada found resuspension rates with spruce on the order of $10^{-7} \text{ m}^{-2} \text{ s}^{-1}$ giving a total resuspension over half a day of 2.5% (Ould-Dada and Baghini, 2001). However, an experiment set at the average outdoor wind speed can not recreate a full range of conditions for resuspension of $\text{PM}_{2.5}$ in the native environment, because we would predict the majority of resuspension will happen at the highest wind speeds. A field study on resuspension in a mixed deciduous forest found slightly faster resuspension rates of $10^{-6} \text{ m}^{-2} \text{ s}^{-1}$ (Wu et al., 1992), which takes into account the natural flux of wind. Wu's finding provides a degree of confidence about the maximum range of $\text{PM}_{2.5}$ resuspension in trees in lieu of the earliest research on resuspension utilizing larger particles. Resuspension that is calculated at a constant rate can be described as a percent of removal of total original deposition, but this percent increases as time continues. Because deposition is the net difference between the particles that deposit and those that are resuspended, it is believed to be more accurate to investigate specific events that are likely to cause resuspension.

Conifers have been demonstrated to be capable of $\text{PM}_{2.5}$ deposition up to ten times that of broadleaf species while their ability to retain particles remains in question (Beckett et al., 2000a; Freer-Smith et al., 2005; Freer-Smith et al., 2004). Spruce resuspension has been quantified at a single wind speed, but it is expected that resuspension plays a larger role at higher wind speeds, because preliminary evidence suggests resuspension is greater at higher speeds (Gillette et al., 2004). Actual deposition is expected to be a smaller fraction than deposition velocity predicts because of concurrent resuspension. Today, the UFORE model still utilizes the official resuspension estimate 50%, so this research in part, is to address this conservative estimate directly.

Specific Aims

For pine, yew, and hemlock:

1. Describe $PM_{3.0}$ Deposition Velocity, and dose-deposition saturation over 50, 100, 200 doses.
2. Describe washoff as a rate of removal of particulates along increasing rainfall.
3. Describe dry resuspension as a linear function over time at three wind speeds, ranging from average to above-average.

My hypothesis is that deposition is a function of total needle surface area. Further, I hypothesize that resuspension will be a function of mechanical energy and that any movement in needles will cause extra resuspension.

METHODS

Summary of Research Objectives

The main objective of this study was to systematically measure the effects of wind and rain on particulate removal from trees within the conifer division. Also measured were particulate deposition velocities for three conifer species. My hypothesis was that species with higher surface area as defined by the needle surface area per centimeter of primary branch would have higher particulate deposition, and would have a higher resuspended fraction as well. A secondary objective was to place this resuspension and washoff information into the context of local meteorology flux and estimate the occurrence of deposition and resuspension as they relate to regularly occurring weather condition maxima. My hypothesis was that within the temperate forest climate of New York, washoff is a more important factor in particle removal from trees than dry resuspension. A third objective was to contribute to the USDA Forest Service's UFORE-D model by providing details of deposition and resuspension on specific tree species.

Three conifers, *Pinus strobus*, *Taxus cuspidata*, and *Tsuga canadensis*, were dosed with KNO_3 particles in the wind tunnel to determine $\text{PM}_{3.0} V_d$, a subset were then treated to a wind event in the wind tunnel or a washoff event and particle removal rates were calculated.

Species selection

The three conifers chosen were Eastern White Pine (*Pinus strobus*), Japanese Yew (*Taxus cuspidata*), and Eastern Hemlock (*Tsuga canadensis*). These species are important to the North East Atlantic region, and represent a range of needle length and width within the conifers and a range of branch flexibility from rigid to supple, which determines its physical reaction to increasing wind speed.

Pinus needles are long and have a small cross-section (90 mm x 0.3 mm) with a slight waxiness. It has five needles per fascicle, each needle a 72° wedge that makes a whole cylinder when all five needles come together. Needle sets are attached directly to the main branch in dense numbers at the tip that thin out further down the branch.

Taxus needles are short and flat with a relatively wide cross-section (20 mm x 2 mm) and a leathery quality. Needles are sharply pointed and two-ranked on straight stem, which branches irregularly, and in landscaping practice is often trimmed into hedge (Dirr, 1975).

Tsuga has the smallest overall individual needles (12 mm x 1 mm) with a soft herbaceous quality. Needles are spatulate, and two ranked on stem that branches flatly into two dimensions (Dirr, 1975).

Needle Surface Area Estimation

Specimens were cut 25 cm from the tip of the branch. Data obtained on the amount of salt on specimens upon dosing and after wind and rain events are normalized by surface area. The average total surface area for each specimen is 0.159 m² +/- 0.27 for *Taxus*, 0.037 m² +/- 0.009 for *Pinus*, and 0.015 m² +/- 0.003 for *Tsuga*, a ratio of 10 : 5 : 1 *Taxus*, *Pinus*, *Tsuga*.

Leaf area was determined empirically through a set relationship between dry weight and surface area determined in preliminary lab analysis. A series of digital images of needles from each species were analyzed using ImageJ software (National Institute of Health, Bethesda, Maryland) to determine surface area. Each species had

ten pictures taken with twenty average size needles per frame, and the surface area was measured by pixel counts with ImageJ. To calculate total surface area, species with flat needles (hemlock and yew) surface area counts were doubled. Pine needles are borne five to a fascicle, so each needle has the cross section of a 72° angle with its included arc, so the surface area of pine was captured on the screen was calculated using geometry as the wedge face with an equal wedge fact plus the rounded perimeter. These same needles were dried at 70 °C in a drying oven, and weighed. The following formulas are the relationship between area and dry weight.

$$Pinus \text{ grams} \times 0.0262 = Pinus \text{ m}^2$$

$$Tsuga \text{ grams} \times 0.02707 = Tsuga \text{ m}^2$$

$$Taxus \text{ grams} \times 0.1386 = Taxus \text{ m}^2$$

Particle selection and preparation

The salt KNO₃ was chosen as a tracer for resuspension experiments because of its low deliquescence. KNO₃ powder was milled in a bar mill to achieve an average diameter of 2.5 μm on a mass basis.

General outline of procedure:

Sample preparation

Samples of the three conifer species were collected from identified trees on Cornell University campus. Tips of branches 25 cm in length were cut, washed in deionized water for 15 minutes, placed in potometers, sprayed with distilled water to the point of runoff, and set out until surface adhering water had evaporated.

Samples were randomly assigned to the wash group, control group, or resuspension group. The wash group was washed only, to determine the amount of background

electrical conductivity on the plant. The control group and resuspension group were placed in the wind tunnel together and underwent a 50-dose deposition event, to be described below. The resuspension group was then subjected to wind and rainfall events. The control group represents the original amount of KNO_3 deposited during the dosing event. Simulations of wind and rain of increasing intensity and duration were given to determine the degree of resuspension.

Dosing

Plant samples were placed in a custom made closed-loop wind tunnel with working section dimensions 60 cm x 60 cm x 240 cm with a custom-made sonic particle disperser used for dosing airborne particulates, and a honey comb straightening element upstream of the working section to reduce turbulence in the air.

Samples were arranged in two different formats for the two trials. In the deposition velocity experiment, samples were supported horizontally in tunnel and pointing into the upstream airflow, approximating position of small branches on tree, and samples were dosed nine at a time. Resuspension trials were more time intensive and required that dosing samples be positioned vertically on bottom of tunnel, and dosed 15 at once.

Dosing was designed to resemble real-world traffic emission events, which occur as short, discrete events with pollutant concentrations 10-100 times higher than background levels for 6-36 seconds. In these experiments, a particulate event was created by injecting a 2-second pulse of KNO_3 powder into the circulating wind tunnel upstream of the specimens. The particles passed through the experimental section at a wind speed of 1.2 m s^{-1} . In each dosing trial, specimens were given fifty pulses during a 30 min period.

Deposition velocity calculation

Deposition velocity was calculated by plotting the average concentration of PM_{3.0} $\mu\text{g cm}^{-3}$ in individual dosing trials against flux of particulates onto the needles per second during the trial, $\mu\text{g cm}^{-2} \text{s}^{-1}$. Deposition velocity is the slope of this line, and is a measure of the amount of PM_{3.0} deposited to the surface independent of exposure concentrations.

Dry resuspension

Dry resuspension trials were conducted in a second wind tunnel uncontaminated by KNO₃ and capable of wind speeds up to 13 m s⁻¹. Trials were conducted at 6.5, 10 and 13 m s⁻¹ (ca. 15 mph, 22 mph, and 30 mph) for 5 minutes, 10 minutes, and 20 minutes. Specimens were then checked for the amount of salt remaining using the method described below. Trials included all three species side by side, to maintain consistency of treatment, and each specific wind speed-duration treatment was replicated five times. Wind speed inside the wind tunnel was confirmed before each trial using a hotwire anemometer at the specimen location.

In Ithaca, the average ground wind speed is 3-4 m s⁻¹ (Northeast Regional Climate Center), rated as a gentle breeze on the Beaufort scale, while 13 s⁻¹ is just below the Near Gale class.

Wash off

Wash off experiments were conducted with a Cornell Sprinkle Infiltrometer (Ogden, van Es and Schindlebeck, 1997, filled with Mega-pure water ® (Barnstead International, Dubuque Iowa) and adjusted to deliver simulated precipitation at 0.367 cm min⁻¹ (8.64 in hr⁻¹). Samples were exposed to precipitation events of 0.367 cm, 0.733 cm, 1.85 cm, and 3.67 cm rainfall.

Over the past 30 years of record in Ithaca, NY, there is measurable precipitation every other day (Northeast Regional Climate Center) and 55% of this rainfall exceeds 0.367 cm/day. Statistically there is a precipitation event equal to 0.367 cm every four days in Ithaca, one equivalent to 0.733 cm every seven days, one equivalent to 1.85 every 25 days, and one equivalent to 3.67 cm or higher every 120 days.

Estimating mass of KNO₃ on leaves

After dosing, samples were washed in 20 ml Mega-pure® water (resistance > 18 mega ohms), and the electrical conductivity (EC) of the water was recorded using a conductivity meter. EC was corrected for the contribution of the washed non-dosed sample then converted to mass of KNO₃ using an empirical calibration equation. Doses were also corrected for the proportion of particulate that is > 3.0 µm, which falls out of the interest of this study, by determining the fraction that is > 3.0 µm in the dosing event. In these research trials, the percent of particles falling into all size classes was recorded, and post hoc correction removes the contribution of particles >3.0 µm. The contribution of large particles ranges from 40%-70% integrated over dosing period in this wind tunnel. The deposition of large particles contributes proportionally to the electrical conductivity changes measured, and it is assumed that the amount of PM_{2.5} can be determined mathematically. An estimate of deposition based on strict PM_{2.5} was not possible because size categories are measured in whole numbers, so the size class reported here is 3 µm aerodynamic diameter and smaller.

At the end of each experiment, specimens were dried at 70 °C in a drying oven, and needles weighed. The needle surface area was determined for each specimen using

the previously reported allometric relationship and the mass of PM_{3.0} as KNO₃ was divided by surface area to determine the loading rate.

Measurement of Particle Concentration in Air

Particle concentration is recorded during the dosing event, by sampling air upstream of the specimens using a Grimm spectrometer, Grimm Model 1.108 aerosol spectrometer (Labortechnik GmbH & Co. Dorfstraße, Germany). The Grimm spectrometer is an optical particle counter that monitors 15 size fractions between 0.3 µm and 20 µm at 6-second intervals in units µg m⁻³.

Pulses, plume decay

The exposure given to tree branchlets is quantified as the concentration in the wind tunnel (average 190 µg m⁻³ +/- 10), moving at a wind speed of 1.2 m s⁻¹, for a duration of approximately 30 minutes. However, exposure to peak concentrations is believed to be more important in PM_{2.5} emission behavior. One pulse of KNO₃ contains approximately 400-600 µg m⁻³ salt at its peak. The concentration of particulates begins at the peak, and decays quickly over 10-15 seconds to a level at which a new plume is added (Figure 2).

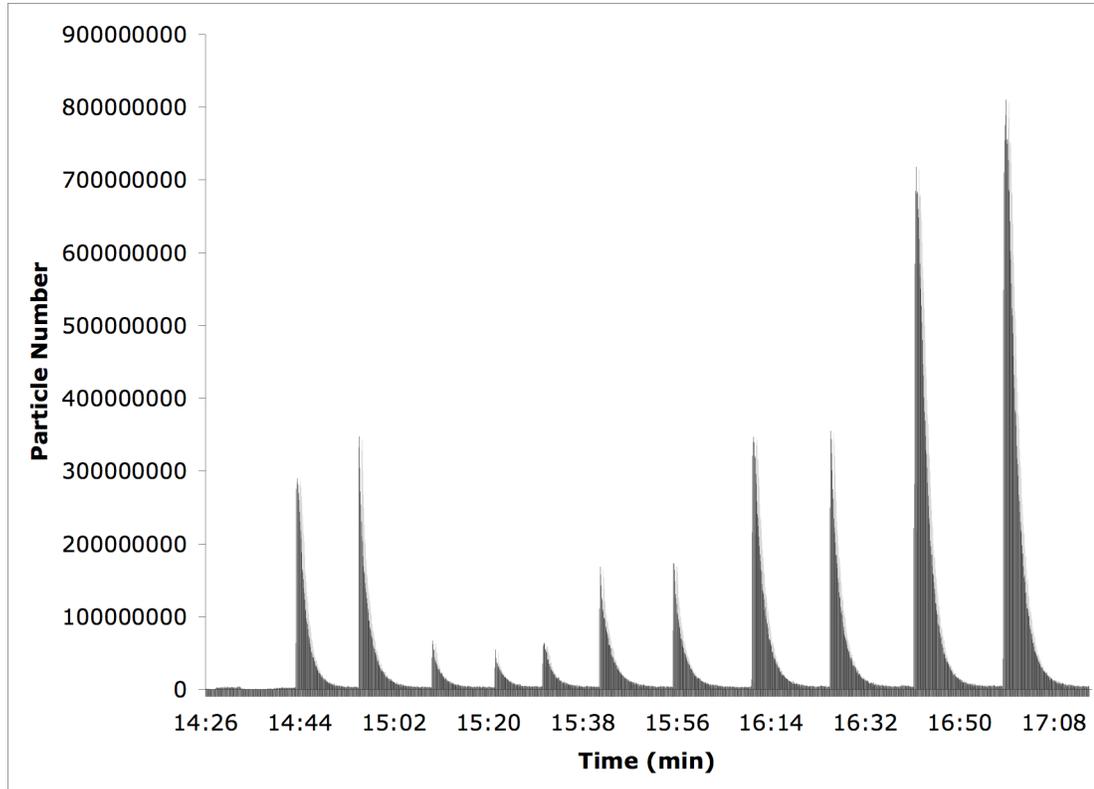


Figure 2. Example of the peak and decay of particle count during dosing events, particles >0.30 μm .

Statistics

Data analysis was performed using JMP 7.0 [®] software (SAS, Cary NC). General linear models procedure was used for analysis of variance (ANOVA) to determine differences in PM_{3.0} deposition after particulate dosing event and differences in response to wind and rain events on three species. SigmaPlot (Systat Software, San Jose CA) was used to fit exponential decay functions to the washoff data. Microsoft Excel (Microsoft, Bellevue, WA) was used to calculate resuspension rates.

RESULTS

PM₃ Deposition

The first experiment, PM_{3,0} deposition over increasing doses of particulates, we find for all three species deposition is positively correlated with exposure dose.

Deposition increases linearly at dose levels of 50, 100, and 200, and there does not appear to be a saturation effect as the dose is increased. When the method of comparison is whole sprigs with approximately the same length primary branch, particulate deposition is statistically similar for all three species (Figure 3). When deposition is normalized to surface area, the species are significantly different in deposition over surface area ($p = 0.048$). Hemlock holds an order of magnitude more particulate per square meter needle than yew and pine (Figure 4).

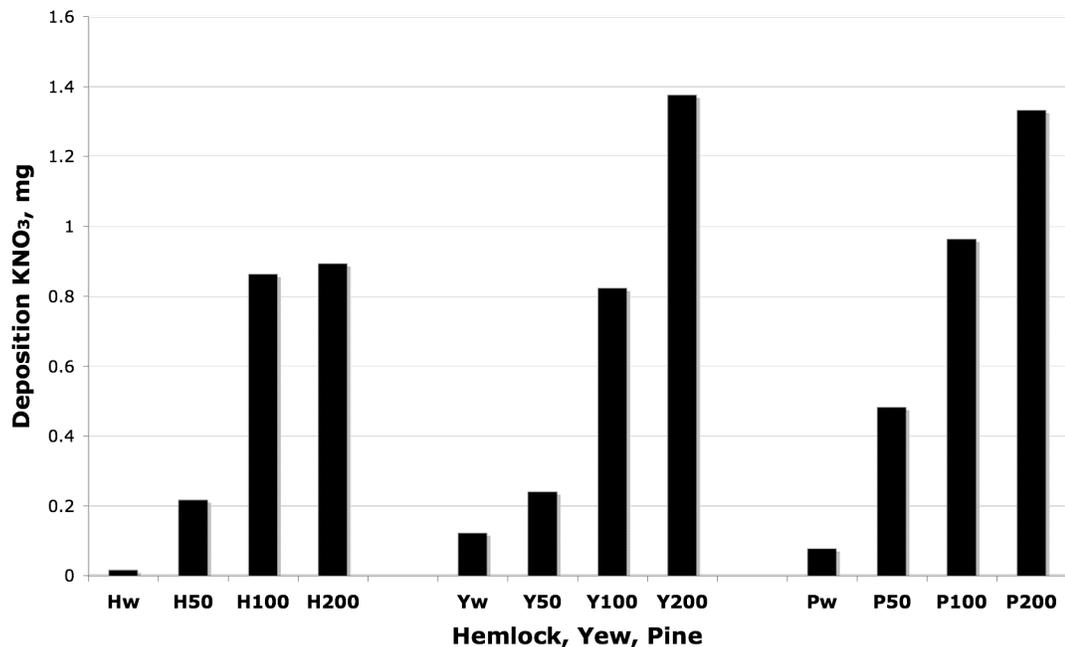


Figure 3. Hemlock, yew, and pine specimens are dosed with KNO₃ particulates at incrementally larger doses of 50, 100, 200, N=1.

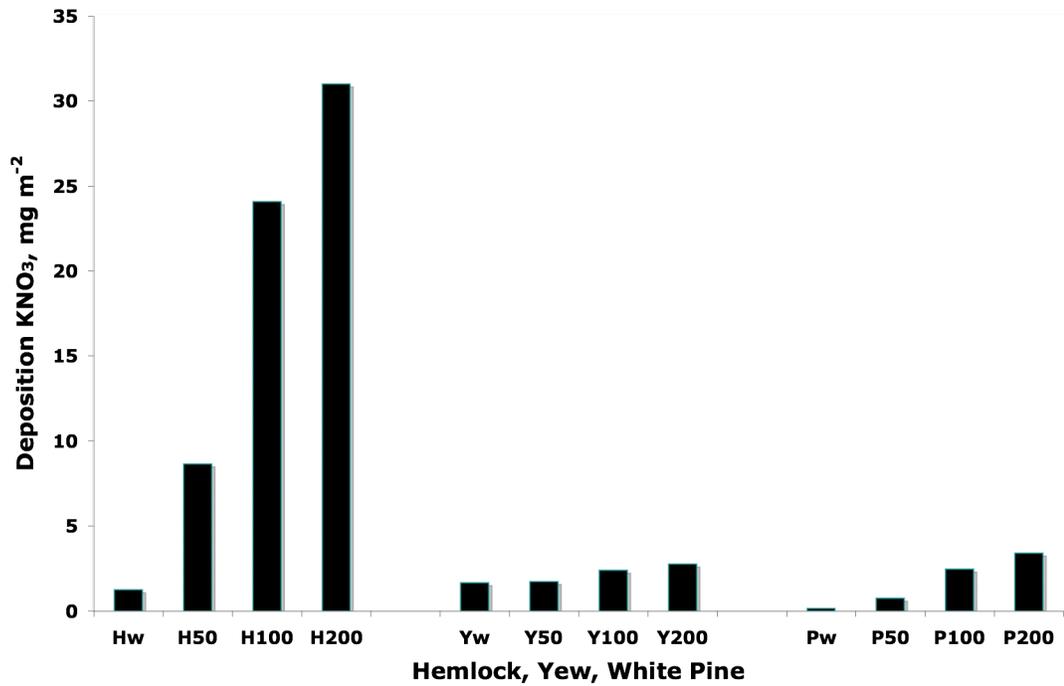


Figure 4. Hemlock, yew, and pine specimens are dosed with KNO₃ particulates in the wind tunnel at incrementally larger doses, deposition by surface area, N=1.

Deposition Velocity

Deposition velocities measured for each species indicate the same general trend found in deposition. Hemlock is 0.02 cm s^{-1} , pine is 0.01 cm s^{-1} , and yew is 0.006 cm s^{-1} .

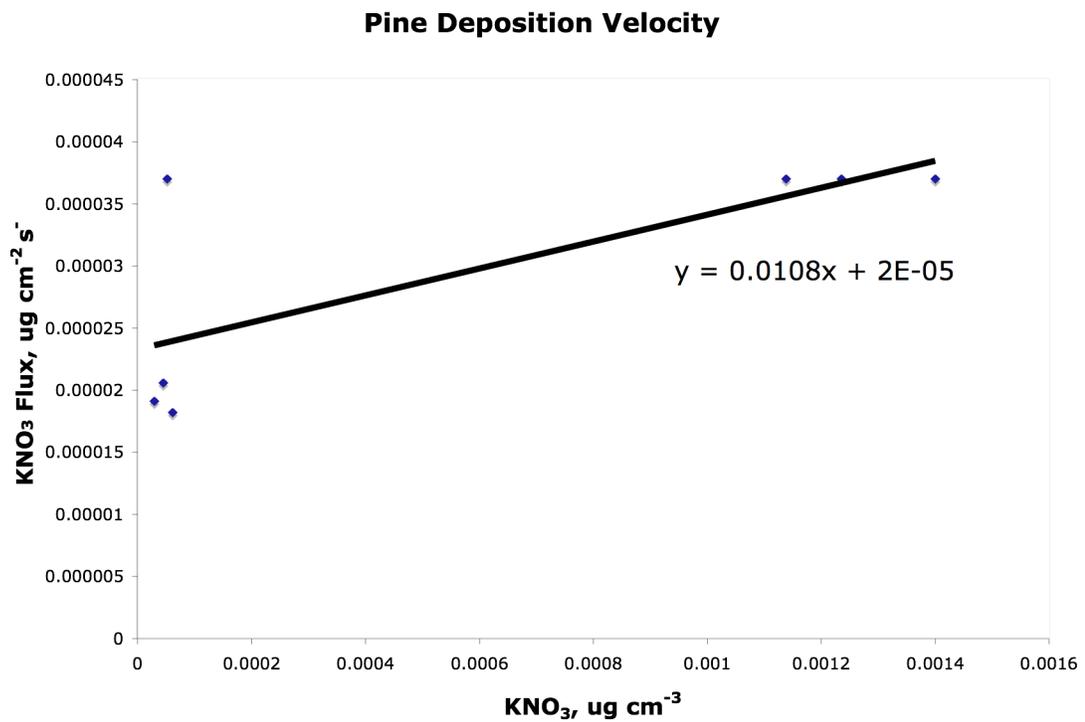


Figure 5. Deposition Velocity for Pine, 0.0108 cm s^{-1} at wind speed 1.2 m s^{-1} from doses of KNO_3 spanning 10 to 200.

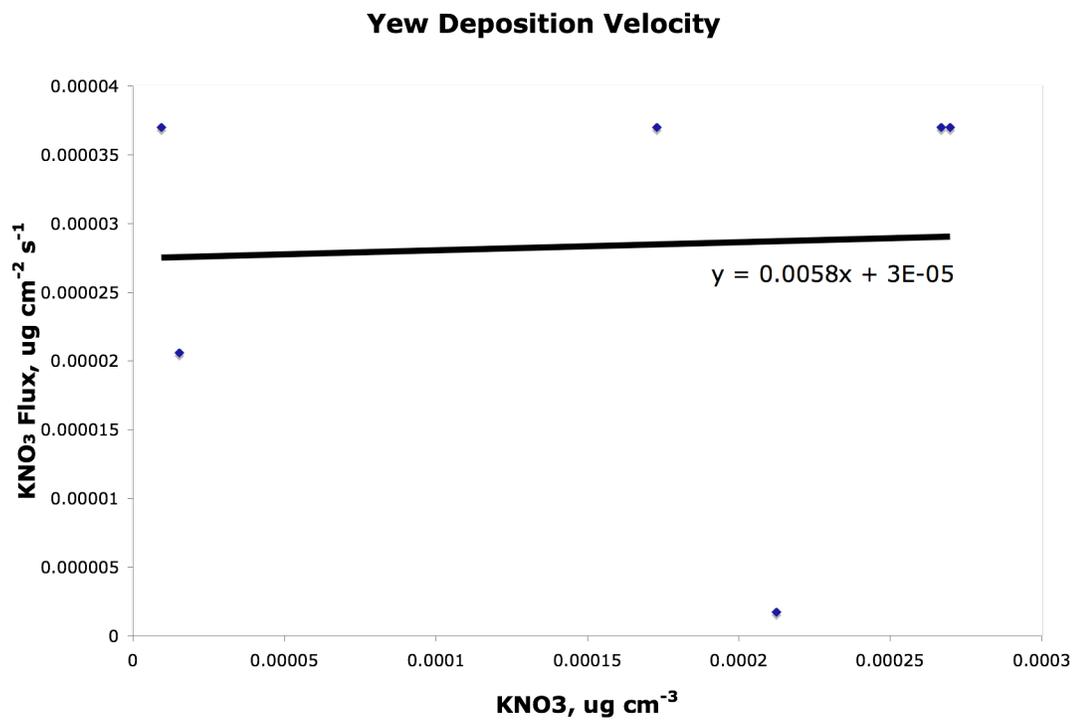


Figure 6. Deposition velocity for Yew, 0.0058 cm s^{-1} at wind speed 1.2 m s^{-1} from doses of KNO_3 spanning 10 to 200.

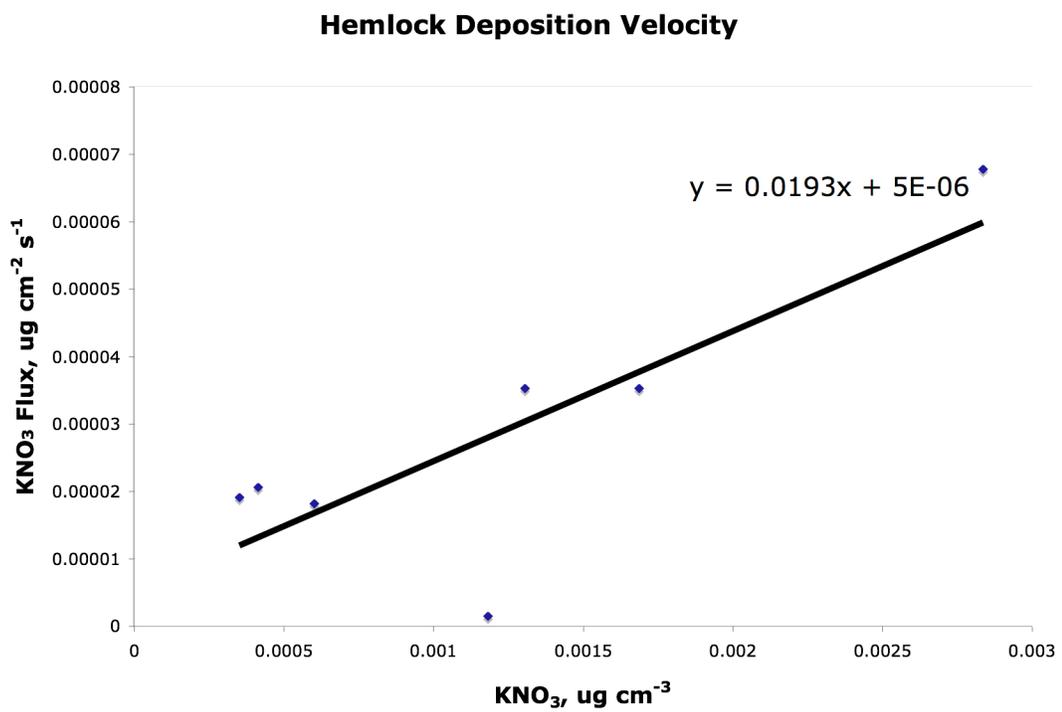


Figure 7. Deposition Velocity for Hemlock, 0.0193 cm s⁻¹ at wind speed 1.2 m s⁻¹ from doses of KNO₃ spanning 10 to 200.

Pinus strobus has a V_d of 0.01 cm s^{-1} , which is one order of magnitude less than that found with *Pinus nigra* in the wind tunnel at a slower wind speed, 0.1 cm s^{-1} (Beckett et al. 2000b), and two orders or magnitude smaller than *Pinus nigra* found out of doors in a woodlot (1.75 cm s^{-1}) or in an urban park (6 cm s^{-1}) (Freer-Smith, 2005). These varieties do have different needle geometries, which can explain the difference in V_d , in various conditions.

Table 2. Deposition Velocity Values

Species	Particle Diameter (μm)	Vd (cm/s)	Wind speed (m/s)	Author
<i>Liriodendron tulipifera</i> & <i>Quercus rubra</i>	0.7	0.056-0.56	Varies (outdoors)	(Wu et al., 1992)
<i>Picea abies</i>	3.8	0.0189 - 0.038	0.8 LAI = 6-11	Biel (2007)
<i>Pinus strobus</i>		0.0108		
<i>Tsuga canadensis</i>	3.0	0.0193	1.2	Pullman (2008)
<i>Taxus japonica</i>		0.0058		
<i>Pseudotsuga menziesii</i>	0.8	0.1-10	Varies (outdoors)	(Gallagher et al., 1997)
<i>Pinus nigra</i>	0.8	0.1	0.7	(Beckett et al., 2000b)
<i>Pinus nigra</i>	2	1.75 (rural) 6 (city park)	Varies (outdoors)	(Freer-Smith et al., 2005)

Washoff

All three species display similar percentages of particle removal at every increment of rainfall, although actual amount of particle washoff varied with original particle load. After the first interval of rainfall (0.367 cm), the percent of total particles removed is 50% for hemlock, 55% for yew, and 62% for pine (amount of salt remaining on leaf is compared against the original dose for percentage removed).

Further rainfall continued to wash off at decreasing rates, with final percent removed reaching 83% for hemlock, 89% for yew, and 87% for pine.

Table 3. Washoff values. Salt remaining on specimen, mg m^{-2} after rain event (standard error in parentheses).

Rainfall (cm)	Pine	Yew	Hemlock
0	20.04 (7.2)	4.37 (1.0)	33.4 (6.7)
0.367	7.6 (1.2)	2.0 (0.5)	16.8 (2.3)
0.734	5.7 (2.0)	1.3 (0.1)	11.2 (2.5)
1.835	3.0 (0.8)	1.3 (0.4)	5.9 (2.0)
3.670	3.9 (1.0)	0.5 (0.2)	9.3 (3.2)

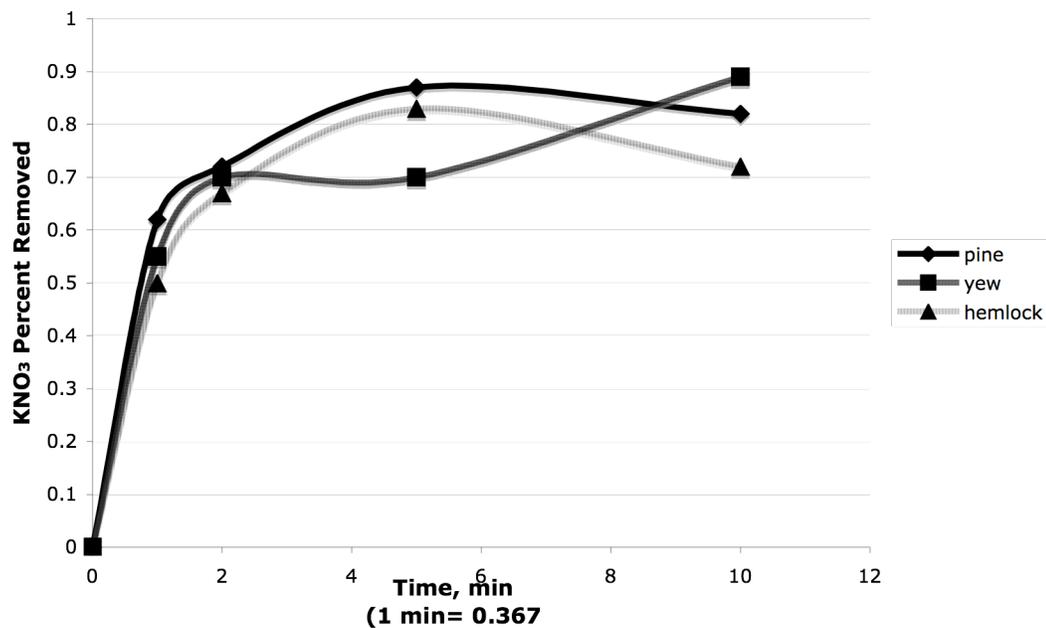


Figure 8: Pine, Yew, Hemlock demonstrate similar rates of particle removal for rain washoff.

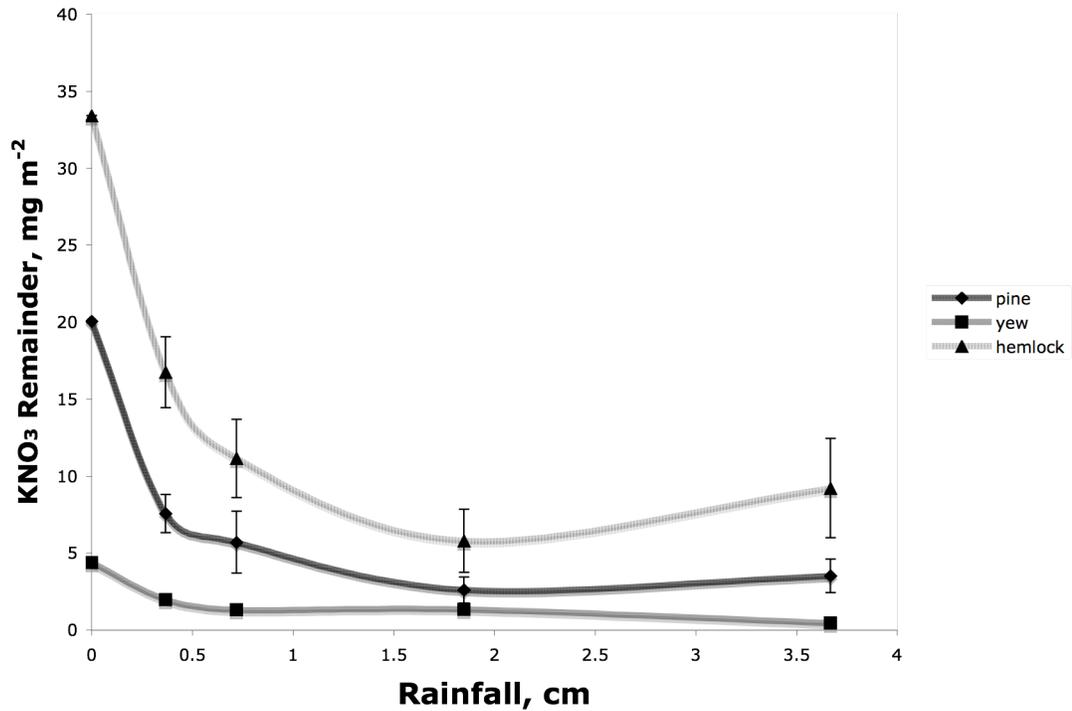


Figure 9. Hemlock, Pine, and Yew demonstrate different amounts of particle removal for deposition, with correspondingly different rates of particle removal for during simulated rainfall events.

Species begin with different salt loading, yet all three reach similar endpoints following simulated rainfall. A maximum of 25 mg m⁻² is washed off of hemlock, 15 mg m⁻² is washed off of pine, and 3 mg m⁻² is washed off of yew. Washoff rates are expressed as a 3 parameter exponential decay, in the general form

$$y = y_0 + ae^{-bx} \quad \text{Equation 2.}$$

Table 4. Washoff of salt by rainfall, expressed as an exponential decay function.

	y_o	a	b	R²
Pine	4	16	4.17	.69
Yew	1	3	3.23	.71
Hemlock	8	25	2.56	.75

In the exponential decay function (Equation 2), x = rainfall (cm) and y = particulate washoff (mg m^{-2}). The parameter describing washoff kinetics, “b” shows pine has the fastest washoff rate, followed by yew and then hemlock. The parameter describing the starting amount of salt, “a” spans an order of magnitude, reflecting the range of deposition between these species. Similarly, Figure 8 shows the rate of proportional washoff for all three species is similar throughout the rainfall event, while Figure 9 shows that the amount of salt removed varies. The similarity between washoff rates suggests that morphological variation does not influence the effect of rainfall on plant $\text{PM}_{3.0}$ washoff. An ANOVA of washoff decay rates and species indicates no significant difference among the species.

Dry Resuspension

In dry resuspension, all three species seem to follow different trends. Pine demonstrates increased resuspension rates as windspeed increases, while resuspension rates in yew are slight but do not change as wind speed increases, and hemlock does not appear to experience resuspension. However, an ANOVA of resuspension rates by species reveals the species do not resuspend at significantly different rates.

Table 5. Resuspension Values. Salt remaining on specimen, mg m^{-2} after wind event.

Windspeed (m/s) & Time (min)		Pine	Yew	Hemlock
Original Dose		7.61 (0.91)	2.96 (0.79)	24.99 (10.0)
6.5	5	7.25 (0.92)	3.09 (0.48)	20.20 (5.76)
	10	8.02 (1.43)	3.48 (0.40)	13.81 (2.99)
	20	8.33 (1.40)	2.08 (0.16)	18.94 (3.13)
10	5	5.61 (0.65)	2.99 (0.57)	18.85 (4.03)
	10	6.35 (1.04)	2.91 (0.54)	23.71 (5.36)
	20	5.95 (0.72)	2.36 (0.43)	24.16 (4.46)
13	5	5.63 (0.77)	2.91 (0.49)	19.68 (4.16)
	10	4.23 (0.82)	2.20 (0.34)	18.42 (3.58)
	20	4.00 (0.45)	2.44 (0.48)	25.32 (6.90)

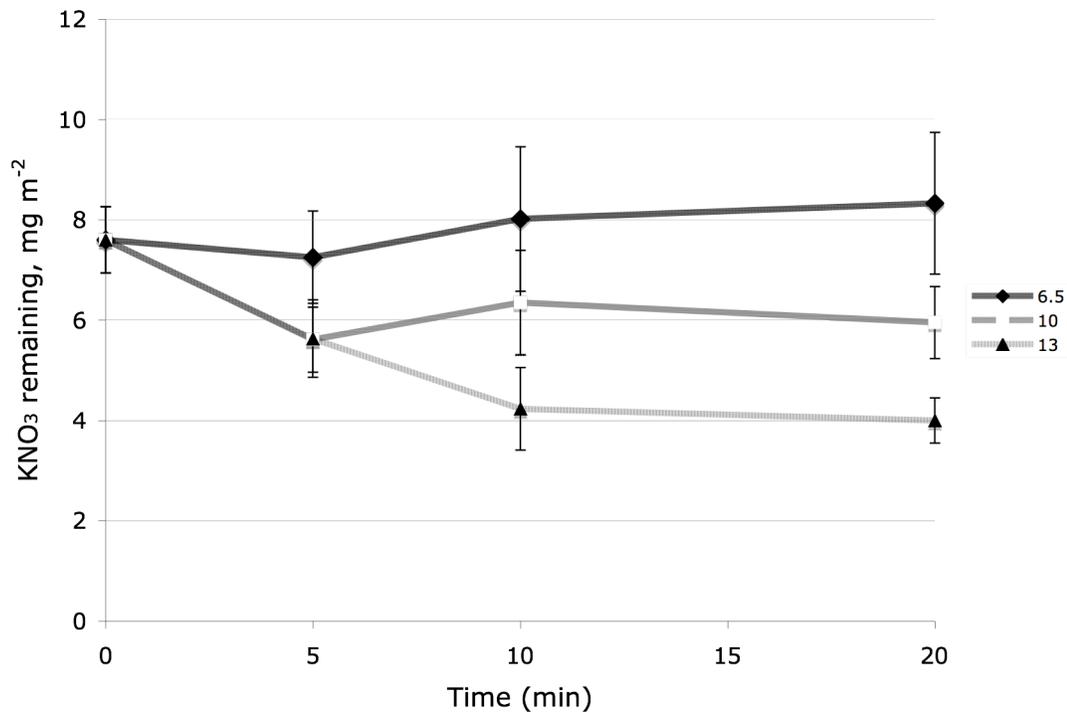


Figure 10. Pine resuspension at 6.5, 10, 13 m/s at 5, 10, 20 minutes, including dosed original.

After twenty minutes in a wind event of 10 m s⁻¹ pine has an average resuspension of 22% (+/- 9%) compared to the original dose, and after twenty minutes in 13 m s⁻¹ pine has an average resuspension of 47% (+/- 6%), while at 6.5 m s⁻¹, no resuspension has occurred.

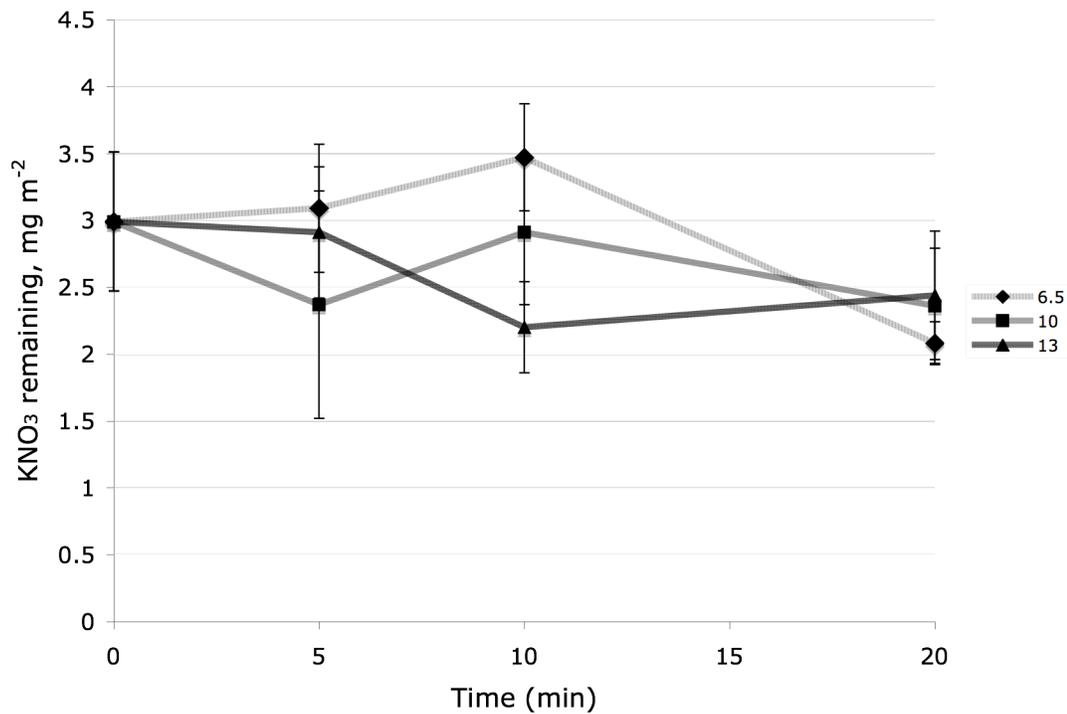


Figure 11. Yew resuspension at 6.5, 10, 13 m/s at 5, 10, 20 minutes, including dosed original.

After twenty minutes in a wind event of 10 m s⁻¹ yew has an average resuspension of 21% (+/- 15%) compared to the original dose, and after twenty minutes in 13 m s⁻¹ yew has an average resuspension of 18% (+/- 16%), while at 6.5 m s⁻¹, 30% resuspension occurs (+/- 5%).

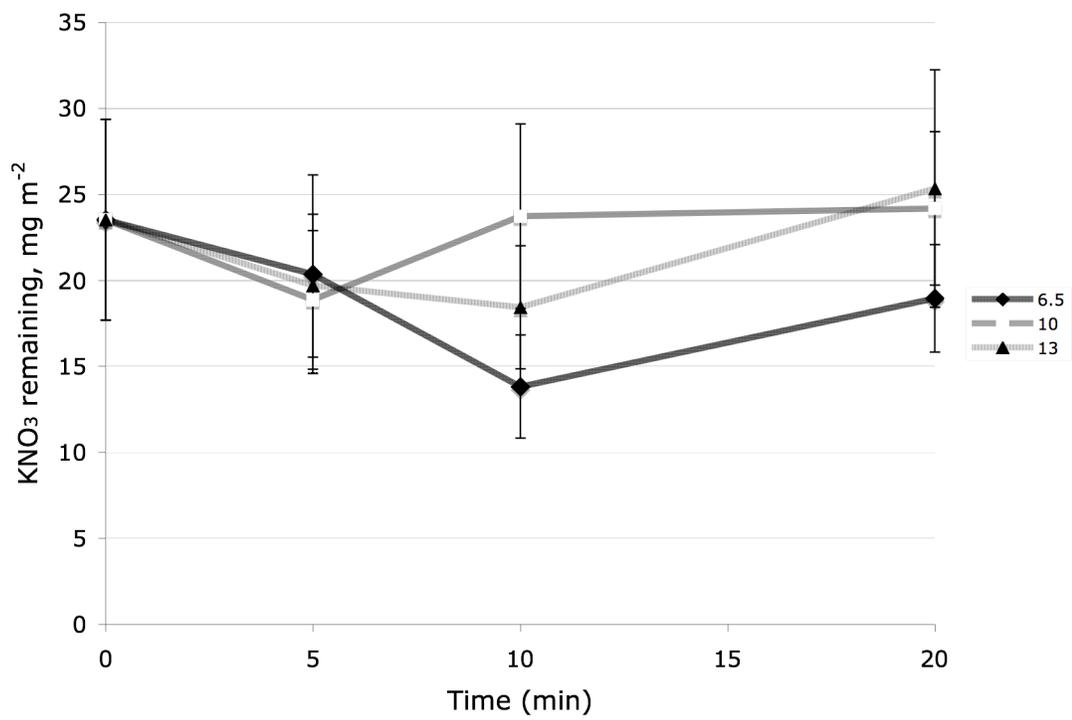


Figure 12. Hemlock resuspension at 6.5, 10, 13 m/s at 5, 10, 20 minutes, including dosed original.

Resuspension values were fit to linear slopes, the rate of resuspension. Low R^2 values for all three species indicate a high degree of variability for all three (Table 6).

Table 6. Resuspension rates expressed as a linear flux function.

	Wind speed m s^{-1}	Flux, $\text{mg m}^{-2} \text{s}^{-1}$	R^2
pine	6.5	3×10^{-4}	0.0021
	10	2.4×10^{-3}	0.1009
	13	4.3×10^{-3}	0.2700
yew	6.5	5×10^{-4}	0.0324
	10	4×10^{-4}	0.0208
	13	5×10^{-4}	0.0327
hemlock	6.5	5.2×10^{-3}	0.0476
	10	$- 8 \times 10^{-4}$	0.0013
	13	$- 5 \times 10^{-4}$	0.0040

Pine demonstrates increasing resuspension rates as wind speed increases, from $3 \times 10^{-4} \text{ mg m}^{-2} \text{ s}^{-1}$ at 6.5 m s^{-1} to $2.4 \times 10^{-3} \text{ mg m}^{-2} \text{ s}^{-1}$ at 10 m s^{-1} and then twice as high at 13 m s^{-1} to $4.3 \times 10^{-3} \text{ mg m}^{-2} \text{ s}^{-1}$. Yew has a similar resuspension rate to pine at 6.5 m s^{-1} but this rate remains the same at 10 m s^{-1} and 13 m s^{-1} . For hemlock, particle removal is substantial at 6.5 m s^{-1} . Hemlock has negative resuspension flux values at 10 m s^{-1} or 13 m s^{-1} , which indicates no apparent resuspension and that the variability within the specimens is greater than any trend of resuspension.

Specimen behavior in wind tunnel

Winds of 10 and 13 m s⁻¹ were strong enough to cause specimens to move under the force of the wind. Pine, with its single primary branch to which all needles are attached, remained rigid in the wind, and each needle shook or vibrated in the air, some needles hitting against each other. Needle movement, in which mechanical energy moves the needle from the base, is correlated with resuspension. Pine needles showed the most movement, with the furthest oscillation at the tip. Hemlock, with its very flexible branches, moved and swayed as one unit with primary, secondary, and tertiary branches absorbing the force of the wind, allowing the needles themselves no movement. Yew exhibited a movement intermediate between pine and hemlock, with secondary branches moving and occasionally fluttering needles.

In summary, hemlock appears to be the most efficient at depositing particles by surface area of needle, then pine and yew. When exposed to wind events, none of the species resuspends PM_{3.0} to any significant degree.

Meteorology of Ithaca, New York

Within the urban tree canopy, resuspension happens in the context of meteorological conditions and peaks of activity in wind and rain. The wind and rain events simulated in these experiments are representative of the scale of events that occur in Ithaca, New York throughout the course of a year.

In Ithaca, the frequency of rainfall events was calculated by taking the number of days in thirty years the precipitation was equal to or greater than the category (0.367, 0.720, 1.85, 3.67 cm) and dividing this number by the number of months total to arrive at the average number of days per month this rainfall event occurred.

The smallest event used in this study, 0.367 cm happens on average seven times per month, while the second largest event, 0.720 cm falls four times per month, and the largest event, 3.67 cm falls 0.25 times per month (National Climate Data Center). Another way to represent the rainfall data is with return frequency, which is the number of days before a storm of similar magnitude rains the same amount. Figure 13 is a plot of the four statistical sizes of rainfall events in this study with the number of days in between each.

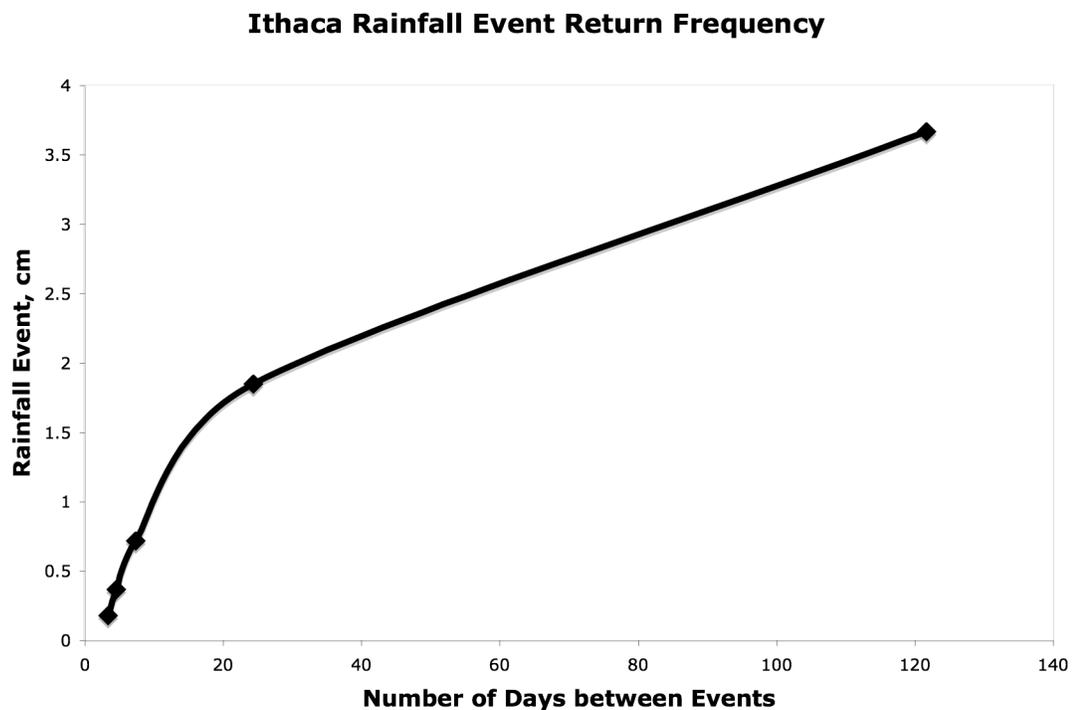


Figure 13. Rainfall events and their return frequency in Ithaca, New York.

In Ithaca New York, it rains an average of once every other day, when averaged over a span of thirty years. One in four days it rains at least 0.367 cm, the smallest rainfall event in this study, in which all three species experienced 50-60% washoff. One in every twenty-five days, it rains at least 2.85 cm, an event that caused 80-90% washoff in this study.

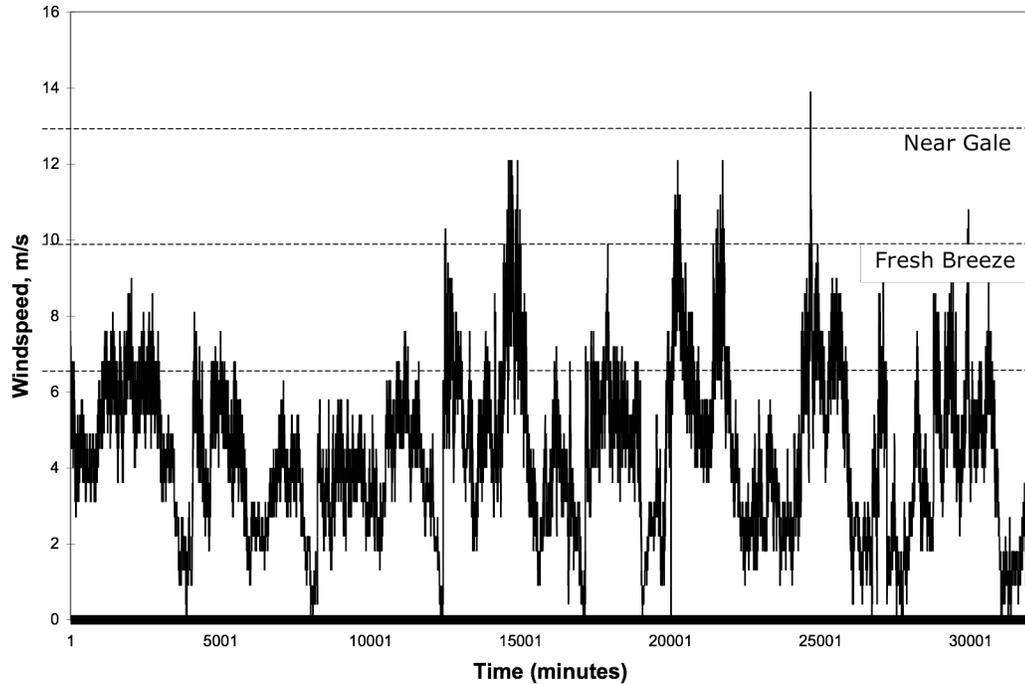


Figure 14. Windspeed by minute in Syracuse, New York for January 2002, 10 m above ground with three wind speeds tested.

An analysis of wind speed by minute for January 2002 in Syracuse (National Climate Data Center) was done with a Fortran program that performed the following tasks: assigned values to each minute of wind, according to parameters defining wind speeds as they are tested in the study: wind speeds tested were bracketed by 1 m s^{-1} . The 6.5 m s^{-1} category is defined as $6-8 \text{ m s}^{-1}$, 10 m s^{-1} is $9-11 \text{ m s}^{-1}$, and 13 m s^{-1} is $12+ \text{ m s}^{-1}$. Using the program, the following wind speed patterns are found. In January, the windspeed is 6.5 m s^{-1} for approximately 13% of the month, 10 m s^{-1} for approximately 1.2% of the month, and 13 m s^{-1} for approximately 0.04% of the month with a windspeed 12 m s^{-1} and over. The fastest wind (13 m s^{-1}) tends to occur for the shortest continuous period of time, an average of 5 minutes, while this period of time extends up to 36 minutes for 10 m s^{-1} and 42 minutes for 6.5 m s^{-1} .

None of the three species experience significant resuspension at 6.5 m s^{-1} . The resuspension that occurs is in pine, during conditions favorable for resuspension, 1.24% of the month.

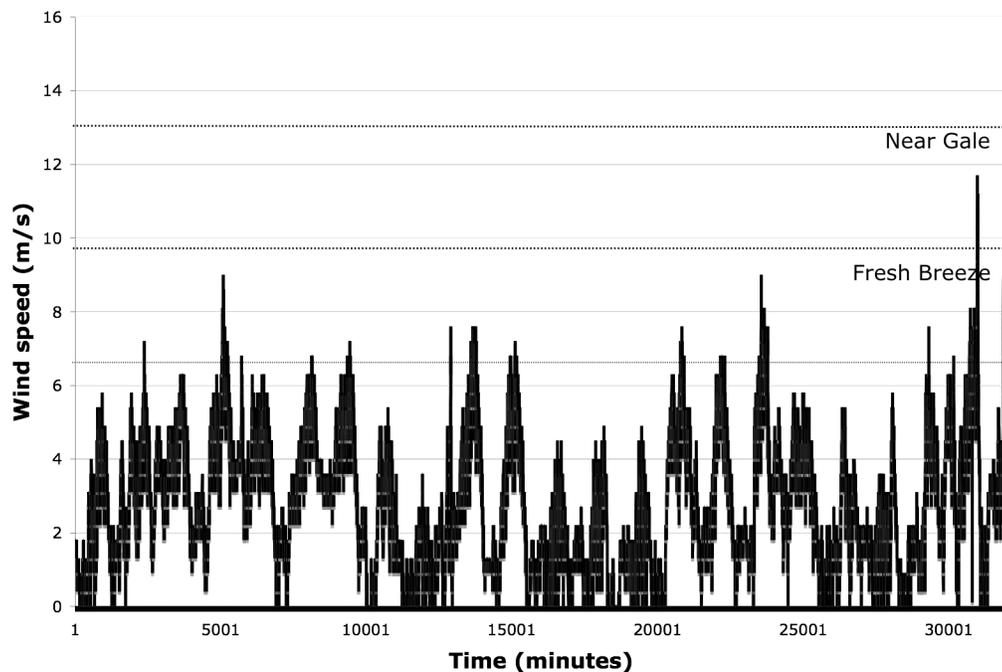


Figure 15. Windspeed by minute in Syracuse, New York for July 2002, 10 m above ground with three wind speeds tested.

In July, the windspeed is 6.5 m s^{-1} approximately 2.8% of the month, 10 m s^{-1} approximately 0.07% of the month, and 13 m s^{-1} approximately $2.3\text{E-}05\%$ of the month. The fastest wind (13 m s^{-1}) tends to occur for the shortest continuous period of time, an average of 3 minutes, while this period of time extends up to 11 minutes for 10 m s^{-1} and 22 minutes for 6.5 m s^{-1} . Wind speed in Syracuse in general remains between $0\text{-}5 \text{ m s}^{-1}$ for 85%-97% of the months analyzed. . Of the species tested, only pine would resuspend, and this happen occurs in 0.07% of July. The meteorological events that determine resuspension and washoff in the natural world suggest that the fate of particles depositing onto trees is being washed off by

water within a few days, and intermittent resuspension will bring an inconsequential amount of $PM_{3.0}$ back into the air stream.

DISCUSSION

Three conifer species were studied in a wind tunnel to examine their interactions with airborne particles. Each tree's ability to capture, retain and release particles was quantified with deposition velocity and resuspension rates. A detailed description of these results and comparison with the literature is reported here.

The calculated deposition velocity describes the rate of deposition onto a surface, in cm s^{-1} regardless of windspeed and duration. It is the net expression of (i) particles settling on to the leaf, and (ii) particles lifting up and rejoining the flow of air. While the flux away from the leaf is termed resuspension, it is a component of the net flux, and included in deposition velocity. Resuspension was investigated as a separate phenomenon to provide more insight into deposition trends.

In the present study, the needles of pine moved the most, which very likely accounts for its greater rate of resuspension. The pine needle has a length to width ratio of 300, and this length allows it to move freely from its base, making needles prone to contact others and causing mechanical resuspension. The yew needle is thick, and is ten times longer than wide; the needles flutter in high windspeed but do not come into contact with one another. Hemlock has very light needles, ten times longer than wide, that do not move independently in high wind conditions.

Resuspension in pine and yew were expressed as linear rates of decline, yet with R^2 values that range from 0.002 to 0.390, the trends are not robust. I suspect this is due to inherent variability within the phenomenon of complex morphological structure and the turbulent air flow that develops around it. Turbulence is unpredictable and highly varied, therefore, when a process depending on it is observed, we would

expect it to be correspondingly variable. Turbulence facilitates deposition and it is possible that it creates a lift force for resuspension (Ould-Dada and Baghini, 2001). Deposition on all three species has a large degree of variation, the standard deviation ranging from approximately one-third to one-fourth to one-fifth of the original dose averages for pine, yew, and hemlock, respectively. It is conceivable that resuspension occurs but that species specific rates are obscured by a large degree of variation. Obtaining credible estimates of re-suspension will be challenging under the circumstances.

If deposition is a net process, then resuspension would seem to be a component of deposition velocity. When the wind speed increases, more air flow with particles moves across the leaves, and the deposition velocity increases. In fact, a plateau effect has been found in deposition at increasing wind speed for trees starting at approximately 10 m s^{-1} in which deposition velocity remains the same as the wind speed goes above 10 m s^{-1} (Beckett et al., 2000b). Data from Beckett's study indicates that at higher speeds resuspension increases, which in the context of this study will effectively lower the deposition velocity, but only for the long needle pine. **Also found is that resuspension does not occur for one species, which suggests resuspension alone is not responsible for the plateau effect of deposition velocity, and that there is a maximum amount of particles that turbulence can deposit onto the leaf surface.**

The original hypothesis that deposition velocity is proportional to total surface area of vegetation was not supported in this study. Hemlock had the smallest average specimen surface area yet experienced the most deposition, and had the highest deposition velocity. Hemlock's effectiveness at particle collection may be explained by the complexity of its gross structure, a combination of shorter needles

and more secondary and tertiary branching. This suggests that the primary cause of deposition within this set of species is local boundary layer turbulence created as air flows across this complex structure. Beckett has offered a reasonable hypothesis for his findings that conifer's ability to deposit more PM_{2.5} than broadleaves, which is total surface area (Beckett et al., 2000b). But within the species examined in the present study, which are all conifer species, local turbulence seems to drive deposition.

The second hypothesis, that resuspension is driven by mechanical force was supported. The species that experienced the most mechanical disturbance to the needles themselves, pine, experienced the most resuspension of PM_{3.0}. This could be due to the structural design that has a wide transverse cross-section and higher Reynolds number. It is possible that this is the pattern existent within the species studied here, and that trees with 360° needle placement experience more resuspension than two-dimensional branching strategies. However, it must be stated that the experimental design isolated single branchlets and exposed them to wind that they may not experience if they are in the interior canopy of the tree. While there is likely to be mechanical resuspension on any needles protruding out on the edges of the tree, needles buffered from the wind might not experience the same wind speed and turbulence.

In this study washoff behavior in all three species was similar in efficiency. However, field studies suggest that particles do not washoff as easily when on trees. Beckett checked particulate levels on leaves after two days of hard rain, and compared them to end of summer values, finding approximately 25% difference (Beckett et al., 2000a). Pines did tend to lose more particulates than deciduous species, but not significantly. The present study had specimens rest an average of

one hour between particle dosing and rainfall event. The surrogate poly-disperse particles used here might not accurately model behavior for all PM_{2.5} because it was water soluble. However, it should be noted that the similarity of response to rainfall by all three species indicates that there is similarity of behavior.

Overall, trees are not effective at particle removal from the air at the scale of a city. Conifer branches and whole trees have been found to remove up to ten times the PM_{2.5} when compared to broadleaves, yet to exact a meaningful pollution removal for an entire urban area is impossible. For example, models forecasting pollution abatement through the planting of new trees estimate that doubling urban canopy, from 20% of the city beneath canopy to 40% would reduce ozone, a gaseous pollutant, by only 2-4% (Nowak et al., 2000). Where trees can make the greatest difference is in diverting polluted air flow from entering parks, which was found in a European Union study to make a difference in the range of 5-10% PM_{2.5} (De Ridder et al., 2004).

Planting conifers in the urban environment should not be considered a primary method of pollution abatement, because its contribution to air quality is very slight. However, when planted along roadsides and in regions of high concentration of PM_{2.5}, the benefits are arguably more than simply removal, because they can encourage polluted air to flow upwards and disperse pollution away from immediate human exposure (De Ridder et al., 2004). Planting a forest of hemlock would be more efficient at planting a forest of pine, although the results of this study should not be interpreted to mean that hemlock should be planted in favor of pine exclusively, because species diversity is important. Similarly, in residential neighborhoods, yew is recommended to plant as a hedge, although planting hemlock

trees would be a more efficient remover of pollution for the space it occupies on the ground.

In general, it is much more efficient to control pollution at its source rather than after it is in the air. The reduction of particulate emissions from vehicles and stationary sources (including residential wood burning) should remain a top priority. A cautionary note is that trees have been shown to increase pollution on crowded tall city blocks by obstructing dispersive air flow (De Ridder et al., 2004). The urban canopy should be planted in areas where air flow circulation is not impeded.

This research design did not include an aspect of windspeed that does exist with regularity. Wind speed will increase to large gusts 1-3 seconds long that can be twice the average wind speed. These gusts are the most efficient at disrupting the quiet boundary layer, and will act to resuspend particles, as will a shift in wind direction, as particles that were sheltered will now have direct wind exposure. Neither of these aspects of the native setting were included in the study design, therefore, resuspension could be slightly higher because of it.

An extension of this research could study the same treatment conditions for 2-5 hours in the wind tunnel to more fully examine the possibility of long term resuspension trends. The current wind tunnel's motor was limited to no longer than two continuous hours, preventing this study from being done on site.

My recommendations are, just as deposition is treated separately on conifers and broadleaves, so should resuspension for the individual species. Conifers are exposed to wind events strong enough to create significant resuspension for a total

of 1.25% and 0.05% of the months of January and July. The amount of PM_{2.5} resuspended is a very small amount of the total particle capture.

As cities swell in population and air pollution levels remain high, there is a public health crisis brewing that is imperative to tackle, and it is my hope that science and policy-makers can work together to make the urban setting a healthier and better place to live.

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