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Determining the Fate of PM 2.5 Particles Following Capture by Leaves

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ABSTRACT

This project studied PM 2.5 deposition, re-suspension and wash off from leaves under controlled conditions, and dispersion of PM 2.5 near roads and the effect of vegetation on dispersion patterns. Our prior work indicates that net deposition occurs at low rates, with little effect on the concentration remaining in the air. This study found that for leaf types ranging from small needles (hemlock) to broadleaved species (Norway maple) and wind speeds up to 30 mph, re-suspension of PM 2.5 was nil. In contrast, simulated rainfall amounting to ca 0.2 " rinsed > 50% of the PM 2.5 from leaf surfaces and 0.4" reduced leaf loads to background detection limits. Dose-response studies showed that while different leaf types accumulated different amounts of PM 2.5, there was no indication of saturation even with exposure to extreme doses. Outdoor monitoring campaigns show that local PM2.5 sources such as vehicular traffic increase human exposure by orders of magnitude, yet these transient spikes go undetected by official monitors. These local plumes dissipate rapidly with distance regardless of tree cover, but a dense hedge appears to contribute to the magnitude of reduction.

Project objectives:
1. To quantify the effect of leaf area and leaf density on re-suspension of PM 2.5
2. To quantify the relationship between leaf size, dry re-suspension and wash off
3. To quantify the relationship between wind speed dry re-suspension and wash off
4. To evaluate the effect of local sources, distance from those sources and vegetated green space on the frequency and intensity of PM2.5 events

Scope and Justification. Over the past 3 years we have developed techniques using particulate tracers in a custom built wind tunnel that permit precise measurement of PM 2.5 particles on leaf surfaces and also quantifies the effect of leafy branches on airborne particle concentrations as air passes through. While we have found interspecific differences in the ability to capture fine particles we have found that leaf densities up to 10 X those found in nature have virtually no effect on the residual concentration in air. This is an important distinction: even though many particles deposit onto leaf surfaces, the amount is trivial in comparison to the particulate load in the air stream. This unexpected finding contradicts the conventional wisdom that trees are effective filters of airborne particulates and raises the big question, How can this be? Specifically: Do leaves become saturated with particles, releasing them as fast as they are removed? What is the ultimate fate of particles after they deposit on leaves? What are the dry re-suspension rates? What are the wash off rates? Our goals are first, to answer these questions and reconcile inconsistencies between our observations and those of others. Second, because the "housekeeping" roles trees play influence public policy, especially in the area of public health, it is imperative that our mechanistic understanding be correct if policies are to be properly formulated. We need fine scale measurements in landscapes where human exposure to PM actually occurs to assess the contribution of local sources and the influence of vegetation on the concentration and distribution of particulates. A combination of controlled laboratory experiments and field monitoring will help us understand the opportunities and limitations of using vegetation to modify human exposure to fine particulates.

FINDINGS

Objective 1: Leaf area and density effects on dry re-suspension

Using real time analysis of particle plume decay in the wind tunnel has allowed us to graphically show deposition velocity, Vd, for leaves of different species and arrangements in the air stream. The graphic depiction of these experiments plots particle flux to leaf surfaces as a function of ambient concentration in the air, which yields a straight line whose slope is Vd. We analyzed the behavior of discrete size classes that constitute PM 2.5 (the so-called fine particulate fraction, consisting of all particles < 2.5 μm in diameter) and found that the largest particles (2-3 μm) are far less numerous but leave the air more rapidly than the smallest fraction (0,3-0.4 μm) we can measure using optical particle counters. The first finding is well known, but the second contradicts basic diffusion theory, indicating that diffusion through the still boundary layer surrounding a leaf is not rate limiting for larger particles lumped into PM 2.5. Although this has important implications for atmospheric science in general, it is tangential to the objectives of this project.

An example of the Vd relationship suggests that deposition is a net process where as the air gets cleaner, deposition equilibrates with re-suspension and at some point the air gets no cleaner **(Fig. 1).** The X-intercept is the compensation point where deposition equals re-suspension and the y-intercept (typically negative) could be interpreted as the theoretical maximum re-suspension rate into pure air containing no particles. A question that emerged from this series of experiments was, *do leaves ever saturate with particles and cease to take up any more from the air?* To address this question, we dosed leaves in the wind tunnel with varying numbers of pulses extraordinarily high PM concentrations (> 1000μg m-3). Even after 100 pulses there is no sign that accumulation levels off for 3 conifer species **(Fig. 2)**. We use this example because the narrow needles of conifers should facilitate deposition and saturate more quickly than broad-leaved species. There are impressive differences in accumulation among the three species, with hemlock accumulating ca. 10 X the amount of tracer than the others, which accumulate little at all but show clear signs of saturating. It is highly unlikely that leaves in the real world would ever be exposed to the extreme fine particulate loads we were able to impose in the wind tunnel. If leaves do not saturate in the sense that they become net sources of particles, it suggests that the apparent equilibration effect we observed with the Vd plots is due the background air quality of the wind tunnel, not a property of the leaves themselves.

Objectives 2 & 3: Quantifying the relationships among leaf size and shape on dry re-suspension at different wind speeds *and* wash off during simulated events of different intensity.

Broadleaves species. We performed a number of replicated experiments using three tree species with leaves or leaflets spanning the range of sizes typically encountered in the urban forest in the eastern US. Honey locust (Gleditsia triacanthos) has compound leaves with entire leaflets ca. 0.7 cm wide X 3.0 cm long; green ash (Fraxinus pensylvanica) also has compound leaves with entire leaflets ca. 5.0 cm wide X 8.0 cm long; Norway maple (Acer plataniodes) has simple orbicular leaves ca. 12 cm across including lobed margins.

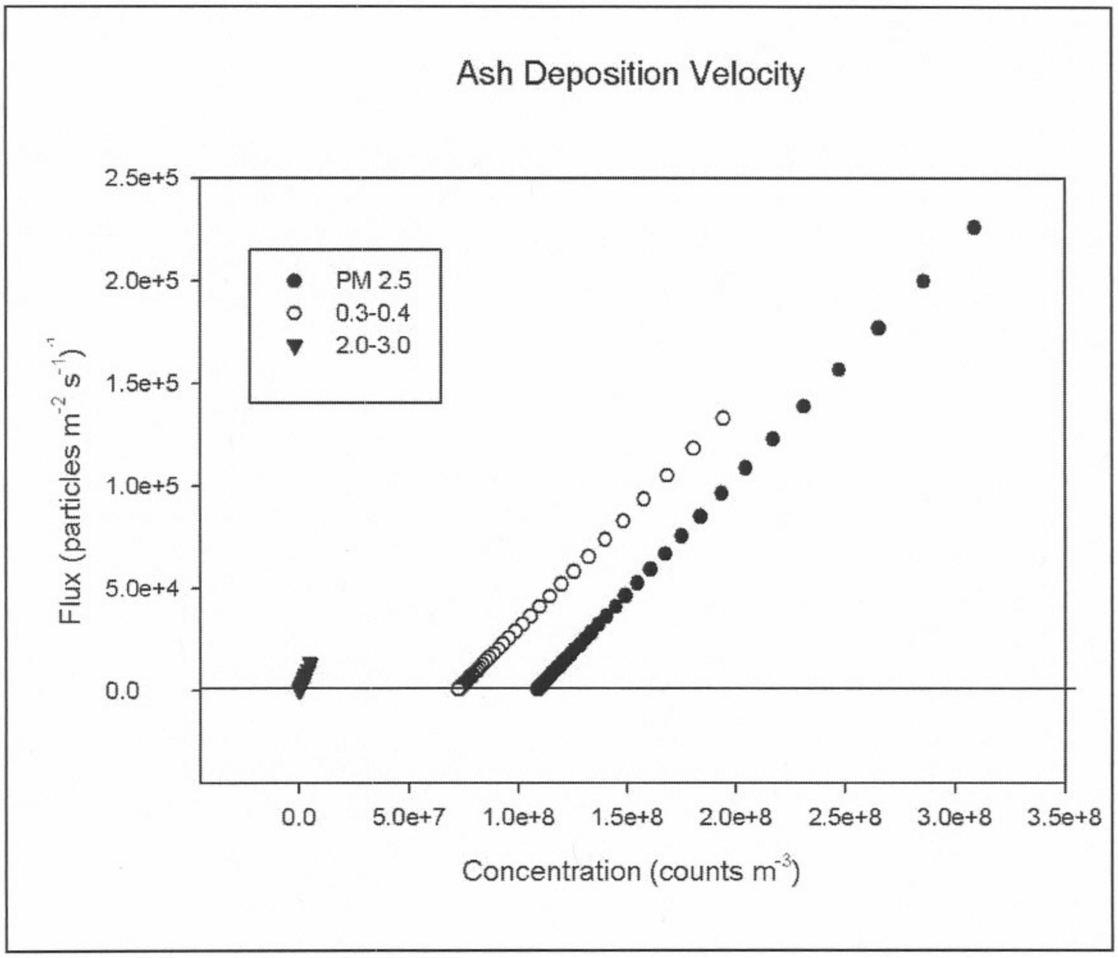


Figure 1. Flux of PM 2.5 components vs. concentration in the wind tunnel. The slopes of these lines are the deposition velocities, V_d.

The general procedure involved applying an exposure dose of PM 2.5 to small branches in the wind tunnel using custom milled KNO_3. Branches had been previously washed in reverse osmosis water and inserted into potometers to maintain turgor during the experiment. Following the dose, branches were transferred to one of two different single pass "clean" wind tunnels capable of delivering speeds up to 5.5 or 13 m s^{-1}respectively. Branches were exposed to wind for varying periods up to 30 minutes, after which the leaves were stripped from the branches and eluted in a know volume of ultra pure water to remove surface electrolytes, after which the electrical conductivity of the wash solution was measured using a conductivity meter. The mass of KNO_3 remaining on the leaf surface is calculated using an empirical regression. The mass of KNO3 remaining was modeled both as exponential and linear functions of time. Surprisingly, we found no evidence of re-suspension even at wind speeds of 13 m s^{-1} (29 mph) for 20 minutes **(Figs. 3 and 4).** There was much scatter across all species, wind speeds and duration of exposure, with the highest r2 for a linear fit across all treatments of only 0.02. We conclude from these findings that re-suspension caused by wind is non-existent regardless of leaf size. This is a significant finding because the UFORE model developed by the USFS has adopted the conservative assumption of 50% re-suspension.

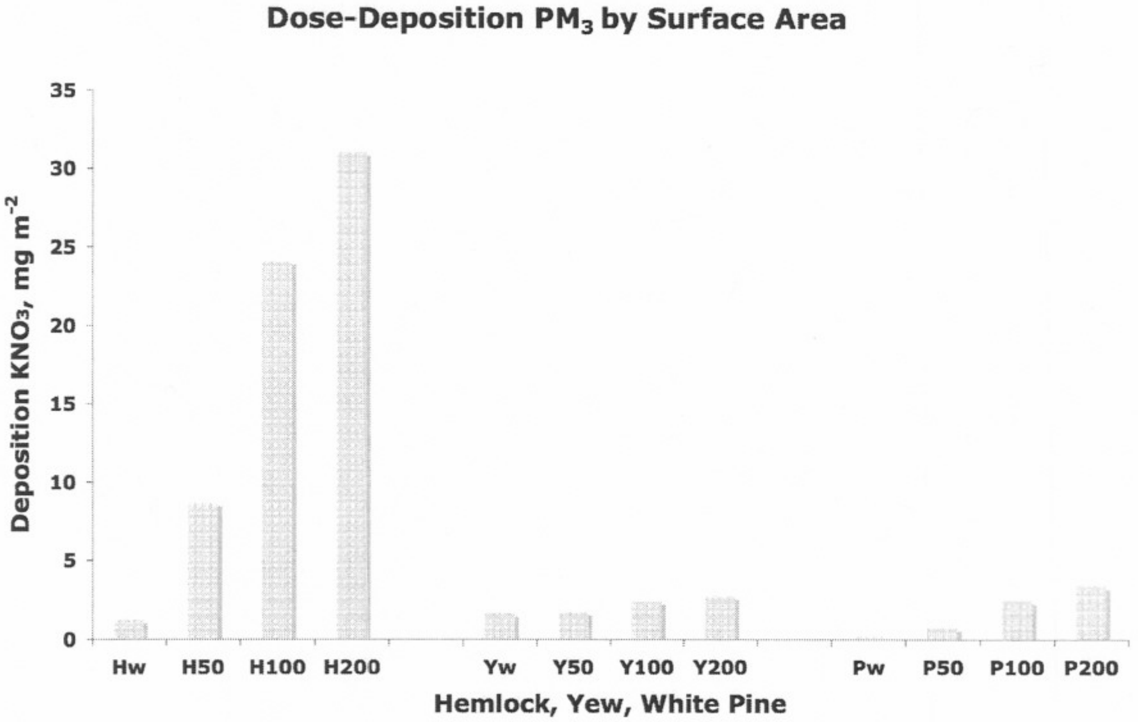
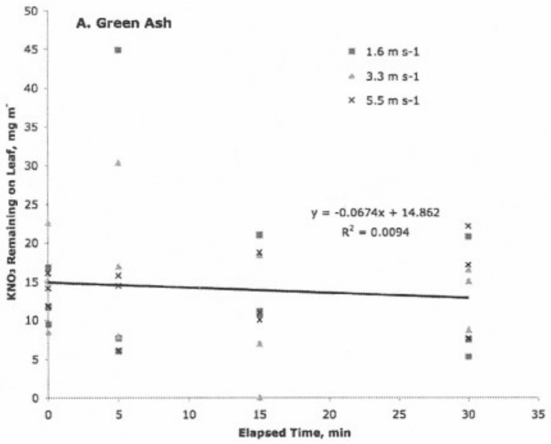
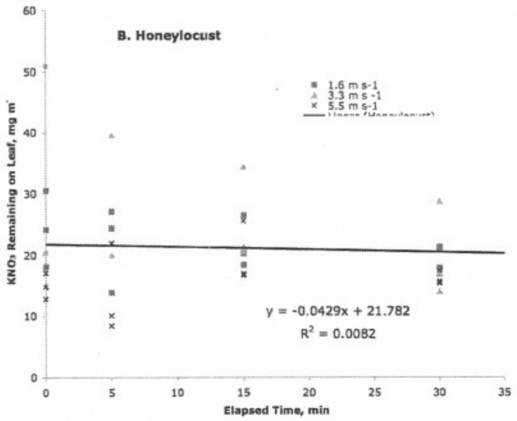


Figure 2. Dose-saturation curves for hemlock (H), yew (Y) and white pine (P) in relation to exposure to 50, 100 or 200 pulses of PM laden air in the wind tunnel.

We performed a parallel set of experiments with the broadleaved species using a rainfall simulator to remove surface KNO_3 from the leaves. The simulator was calibrated to deliver 22 cm h^{-1} and the following dosing using the procedure described for dry re-suspension, branches were exposed to precipitation for 0, 1, 2, 5, or 10 minutes. All three species and treatments had a significant amount of scatter but followed a negative log decay function. The trend in Norway maple was less steep than ash or honey locust **(Fig. 5).** In all cases, > 50% of the accumulated solute deposited on the leaves had washed off after 1 minute of exposure, corresponding to 0.37 cm of rain. While the final mass on the leaves did not decline to zero, it did equal values obtained from leaves washed to achieve a lower baseline for a clean leaf. Because we used mega pure water as opposed to rainwater, it is likely that our wash off values are lower than would be obtained under natural conditions because rain water has a higher content of both soluble and insoluble particles. This does not affect the conclusion that relatively small amounts of rain effectively remove most of the particles.

Conifers. We followed the same procedures detailed above on conifers selected for parallel to represent needle types ranging from short spatulate (hemlock, Tsuga canadensis) to long spatulate (yew, Taxus cuspidata) and long, fine and fascicular (white pine, Pinus strobus). Yew is often used as a hedge, a managed form that potentially could be used for screening laterally transported PM. The low speed wind treatments were omitted with conifers because we found with broadleaved species that low speeds caused no re-suspension.





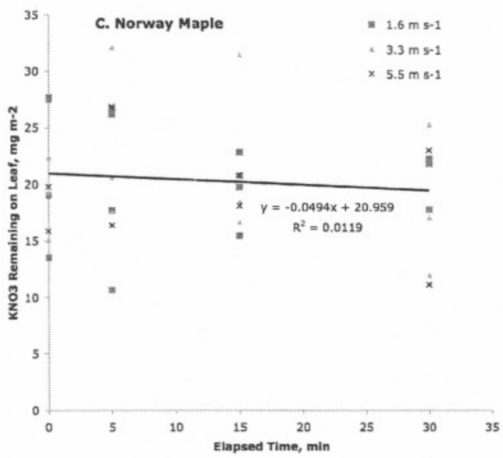
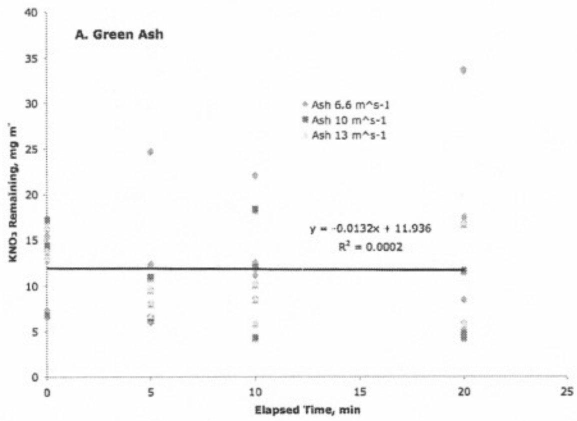
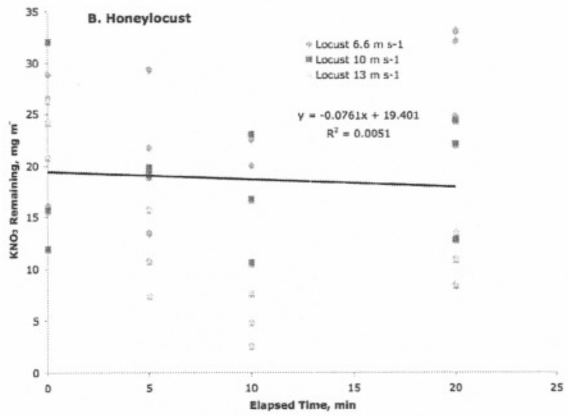


Figure 3. PM2.5 re-suspension from green ash, honey locust and Norway maple leaves at wind speeds varying from 1.6 – 5.5 m s^{-1}.





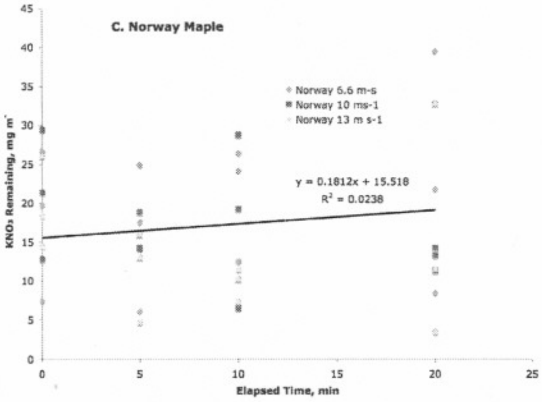


Figure 4. PM2.5 re-suspension from green ash, honey locust and Norway maple at wind speeds varying from 6.6-13 m s^{-1}.

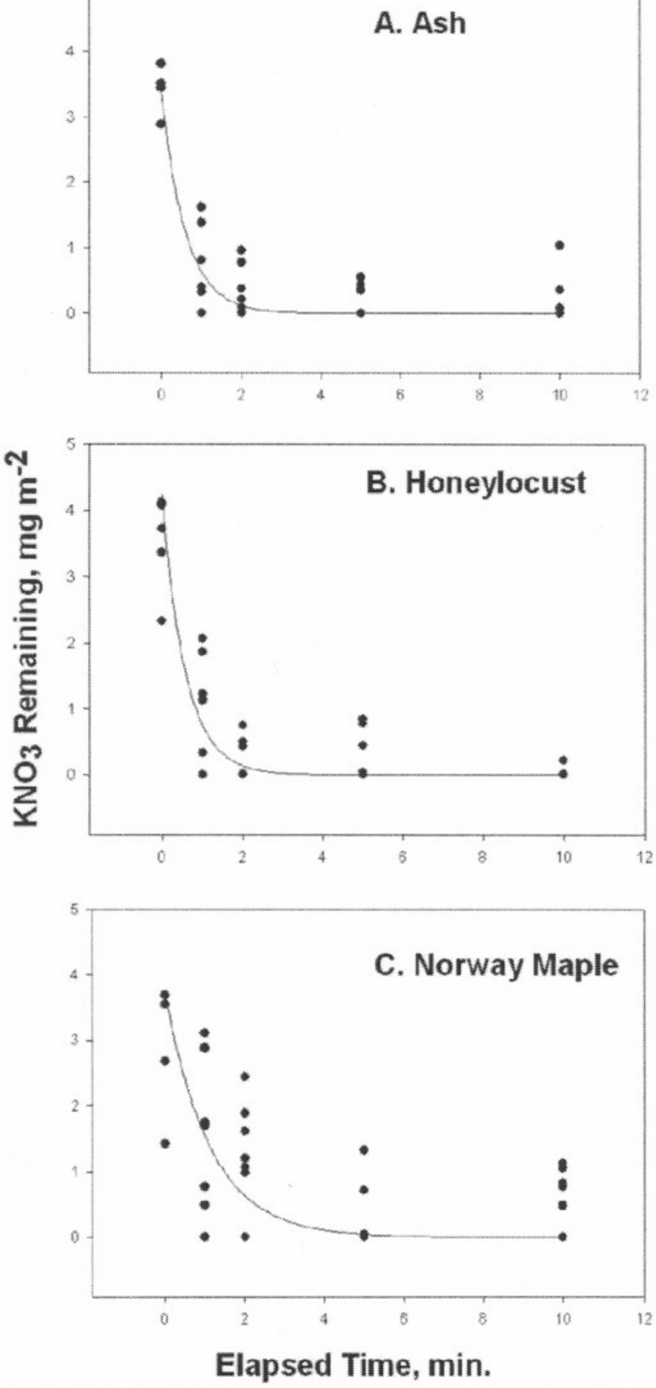


Figure 5. PM2.5 wash off from green ash, honey locust and Norway maple as a function of exposure to simulated rainfall at a rate of 22 cm h^{-1}. 1 min = 0.37 cm, 2 min = 0.73 cm, 5 min = 1.83 cm and 10 min = 3.7 cm of cumulative rainfall.

The pattern of dry re-suspension in conifers resembled those found with broadleaved species, namely, the data showed much scatter and there was essentially no evidence that a detectable mass of particles was removed even after prolonged exposure to air moving 13 m s^{-1} **(Fig. 6).** What is apparent is that the three species accumulated different amounts of KNO3 during the dosing. At the low end, yew on average accumulated ca. 3 mg m-3 while hemlock accumulated ca. 23 mg m^{-2} at the high end.

Wash off was studied as described before for broadleaved species **(Fig. 7).** As with broadleaved species, ca 50% of the surface adhering solutes was rinsed off by 0.37 cm of rainfall, or 0.15". To put this magnitude event in perspective, this is the 4-day return period event in the moist continental climate of Ithaca, NY.

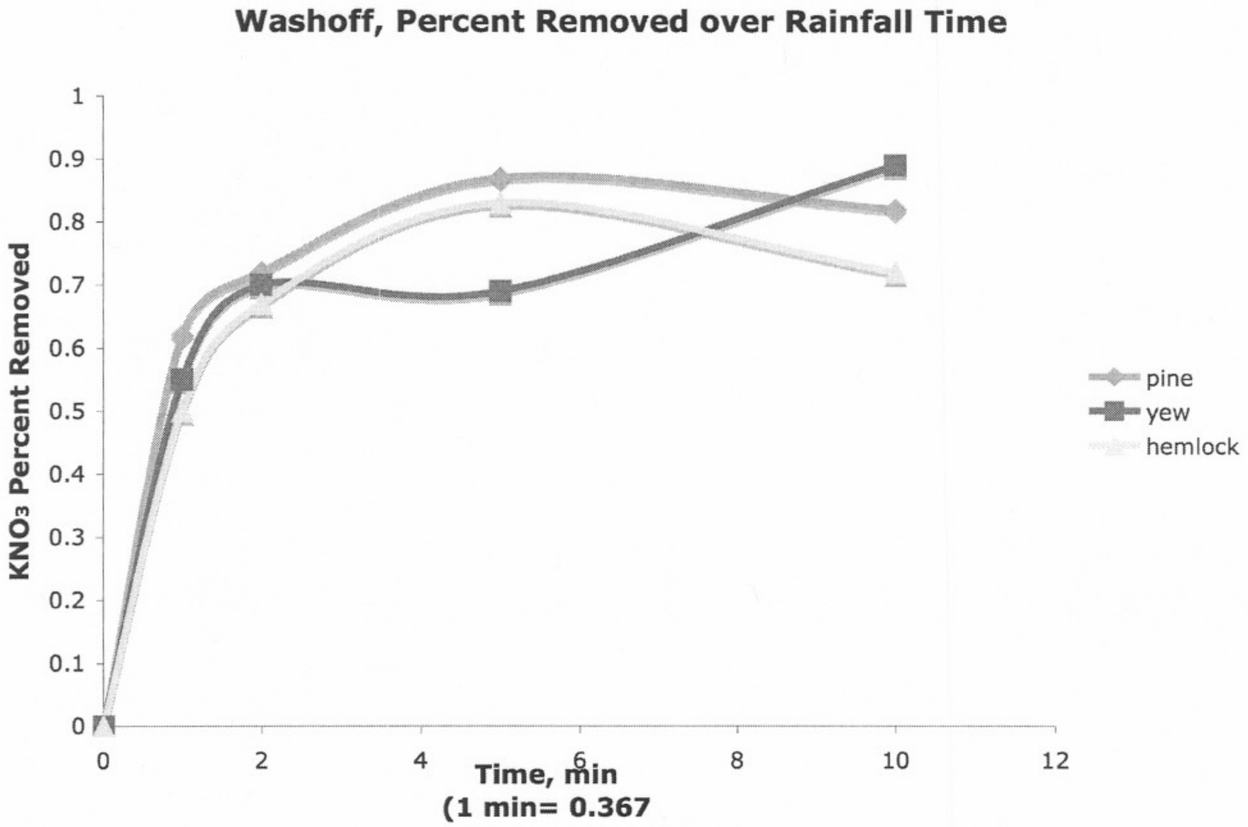
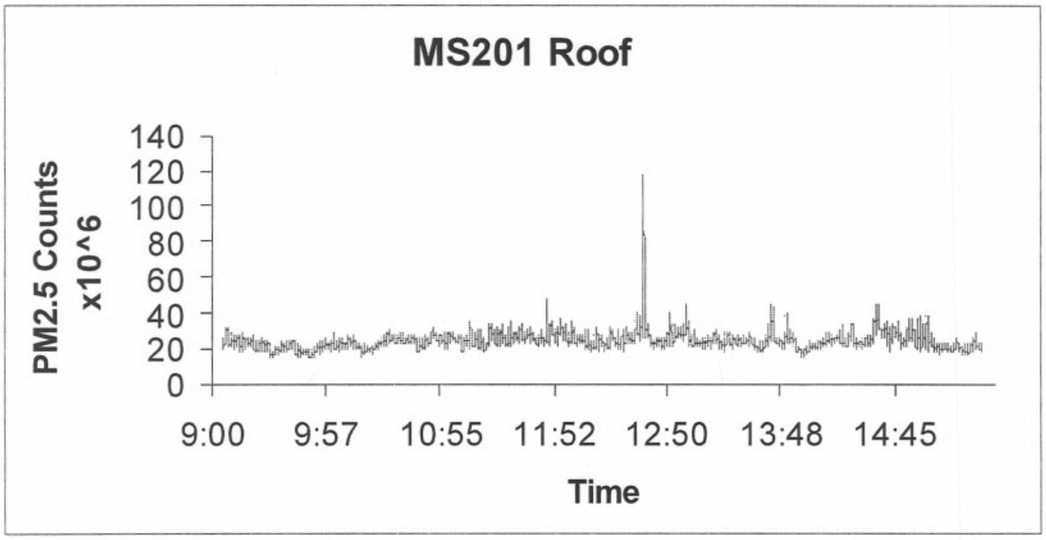


Figure 6. Decimal fraction of PM2.5 (as KNO3) removed by simulated rainfall.

Several conclusions emerge from our controlled studies of dry re-suspension and wash off. First is that dry re-suspension appears not to occur in species selected to bracket the range of leaf sizes commonly found in the urban forest. Furthermore, there was no re-suspension even at wind speeds approaching "Fresh Gale" on the Beauford scale. This finding suggests that perhaps the 50% re-suspension rate adopted by UFORE is unnecessarily conservative. A second conclusion is that small precipitation events effectively rinse soluble PM from leaves to a background detection limit, so leaves are cleaned frequently in mesic climates. A third corollary is that leaves do not saturate with PM even when dosed at extreme levels not usually encountered outdoors.

Objective 4: Evaluate the effect of local sources, distance from those sources and vegetated green space on the frequency and intensity of PM2.5 events

Advisory Panel members were especially interested in the dynamics of pollution at a human scale in the urban environment. Since January, 2007, we have conducted field monitoring campaigns in the South Bronx at 2 public schools where NYDEC PM is monitored and at two city parks. These campaigns show that rooftop PM concentrations are lower than those 2 m above the ground on sidewalks adjacent to schools and that the sidewalk location experiences more extreme events than does the rooftop. These observations demonstrate the strong influence of local sources and horizontal transport from roadways **(Fig. 8).**



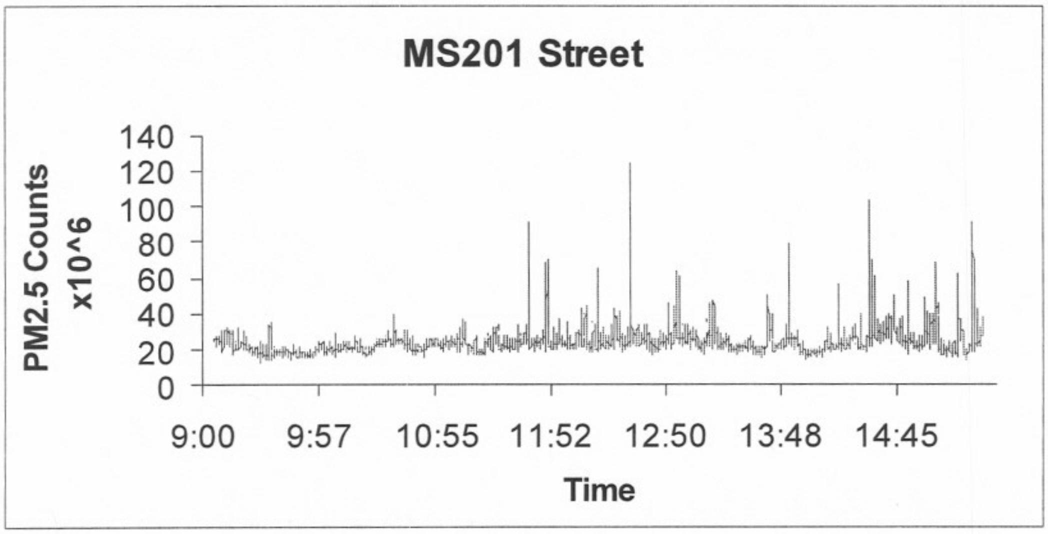
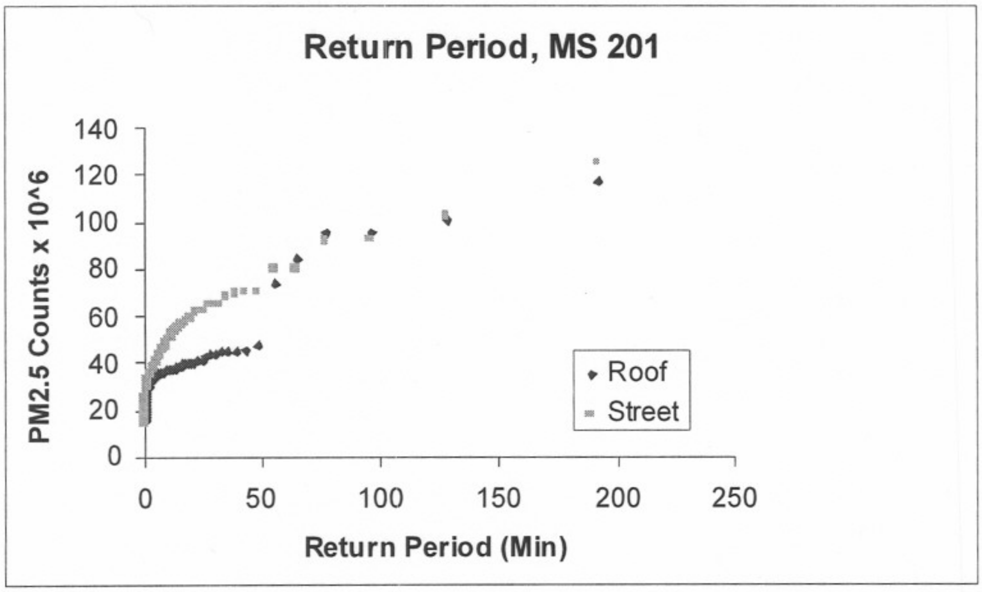


Figure 7. Comparison of PM 2.5 concentrations on the roof of MS201 in Hunts Point, The Bronx and the sidewalk outside the school.

When we subjected these data to a return frequency analysis, we found that the 20 minute return event on the ground was roughly 30% higher than on the roof, indicating that the human exposure risk was greater on the ground than at roof elevation **(Fig. 8).**

During the fall of 2007, we conducted two monitoring campaigns in Baltimore, MD to evaluate the effects of a hedge, street trees, back yard trees and distance from a road on PM2.5 concentration. We found steep declines in PM concentration with distance from roads even in the absence of intervening buildings and vegetation



(Fig. 9,10).

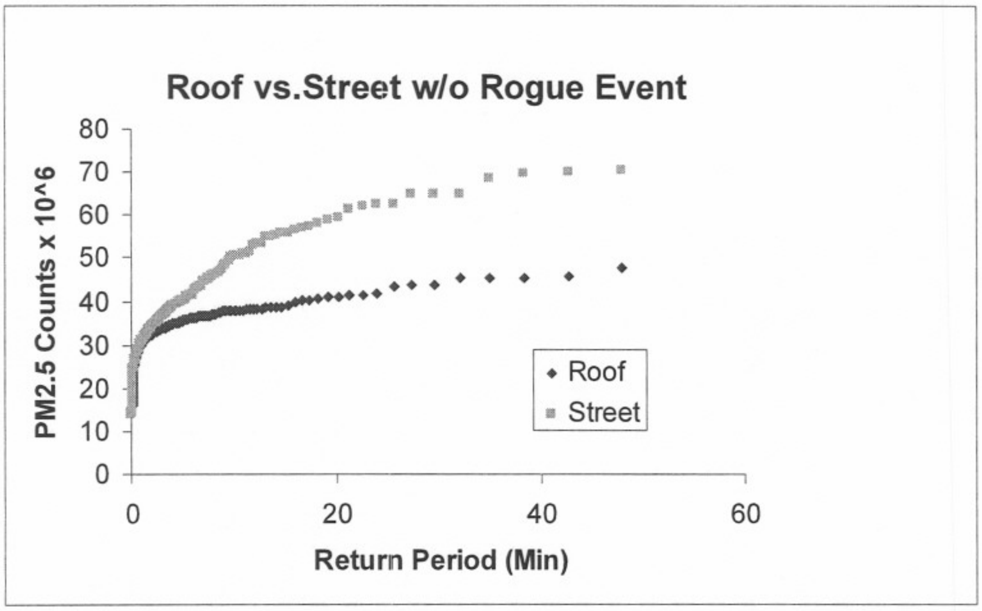


Figure 8. Return periods of PM 22.5 events determined from a short term monitoring campaign. One rogue event was apparent at both sampling locations, indicating that it was likely caused by something other than local traffic (top panel). When this event is removed, the differences between the two locations become more apparent (lower panel).

At the Roland Ave. location, an impressively large 9 m tall Leyland cypress hedge between the road and a sensor resulted in an additional marginal decrease in concentration **(Fig. 9)**. Although we cannot separate the effect of deposition from a wind break effect, in light of our previous wind tunnel studies that showed very little deposition, we conclude that the contribution of the hedge is primarily due to aerodynamics at the scale of the entire hedge, not fine scale deposition to leaves. It is probably that particle-laden air stream is directed up and over the hedge, creating a zone of lower concentration downwind. This interpretation is consistent with recent modeling studies of PM distribution around freeway sound barriers and in urban canyons.

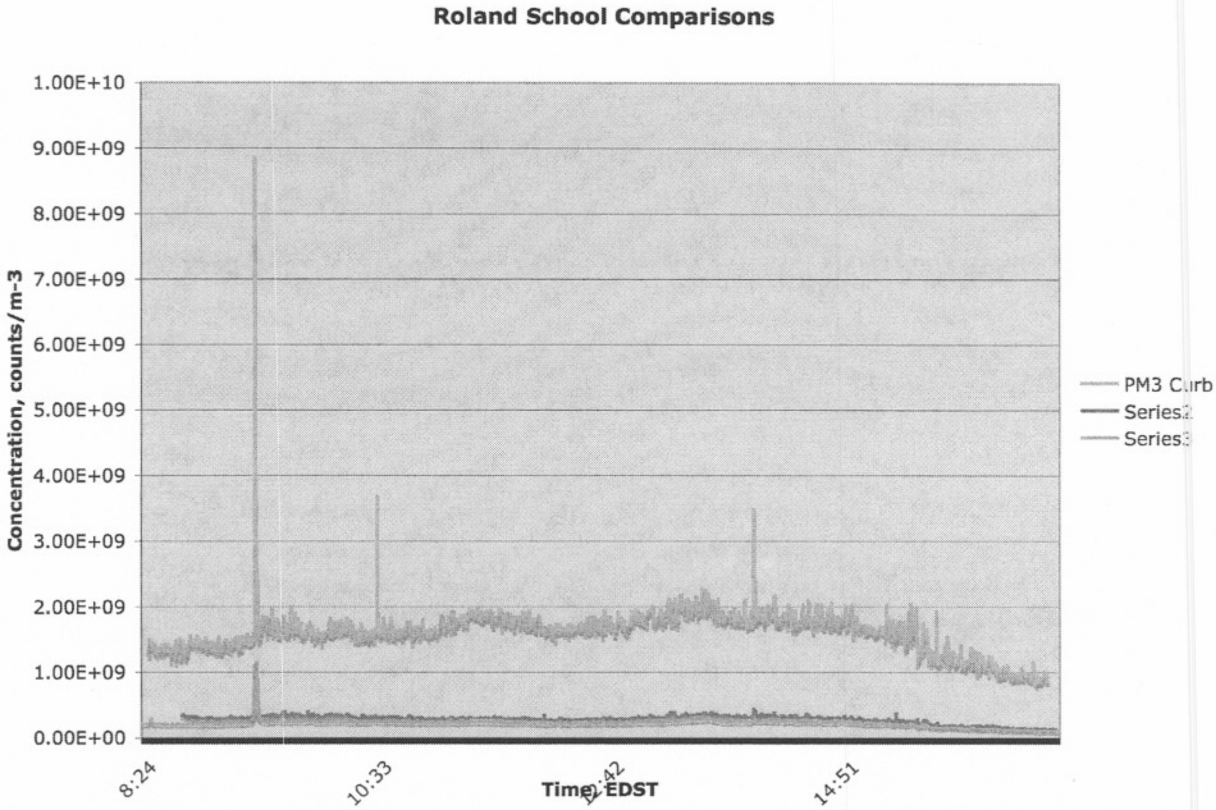


Figure 9. PM2.5 concentrations on Roland Ave., Baltimore, MD during a one day campaign in October, 2008. Curb refers to a curbside monitoring location, Series 2 corresponds to a second monitor in a lawn 15 m from the curb, and Series 3 refers to a third monitor 15 m from the curb behind a 9 m tall Lawson cypress hedge. Measurements taken behind the hedge show an additional incremental reduction in [PM2.5].

It is noteworthy that there are relatively few extreme events on Roland Ave. Although the road is a major north-south artery, there is relatively little heavy truck traffic that often causes transient spikes in concentration.

Like Roland Ave., Fulton Ave. is a major north-south 4-lane artery but closer to the central city. It also carries a heavier volume of heavy truck traffic, which is reflected in the numerous spikes in PM concentration observed **(Fig. 10).** These are virtually undetected at stations back from the curb even in the absence of trees and buildings that might presumably affect PM concentration through deposition or modified air flow patterns.

We have shown only a few examples out of many short term monitoring campaigns to illustrate patterns of fine scale variation in time and space that we typically observe in complex urban environments. We can draw several inferences from them that have implications for urban design and the use of vegetation to abate particulate air pollution. First is the observation that local sources contribute to short term acute exposure doses to humans at scales where they experience their environments during daily activity.

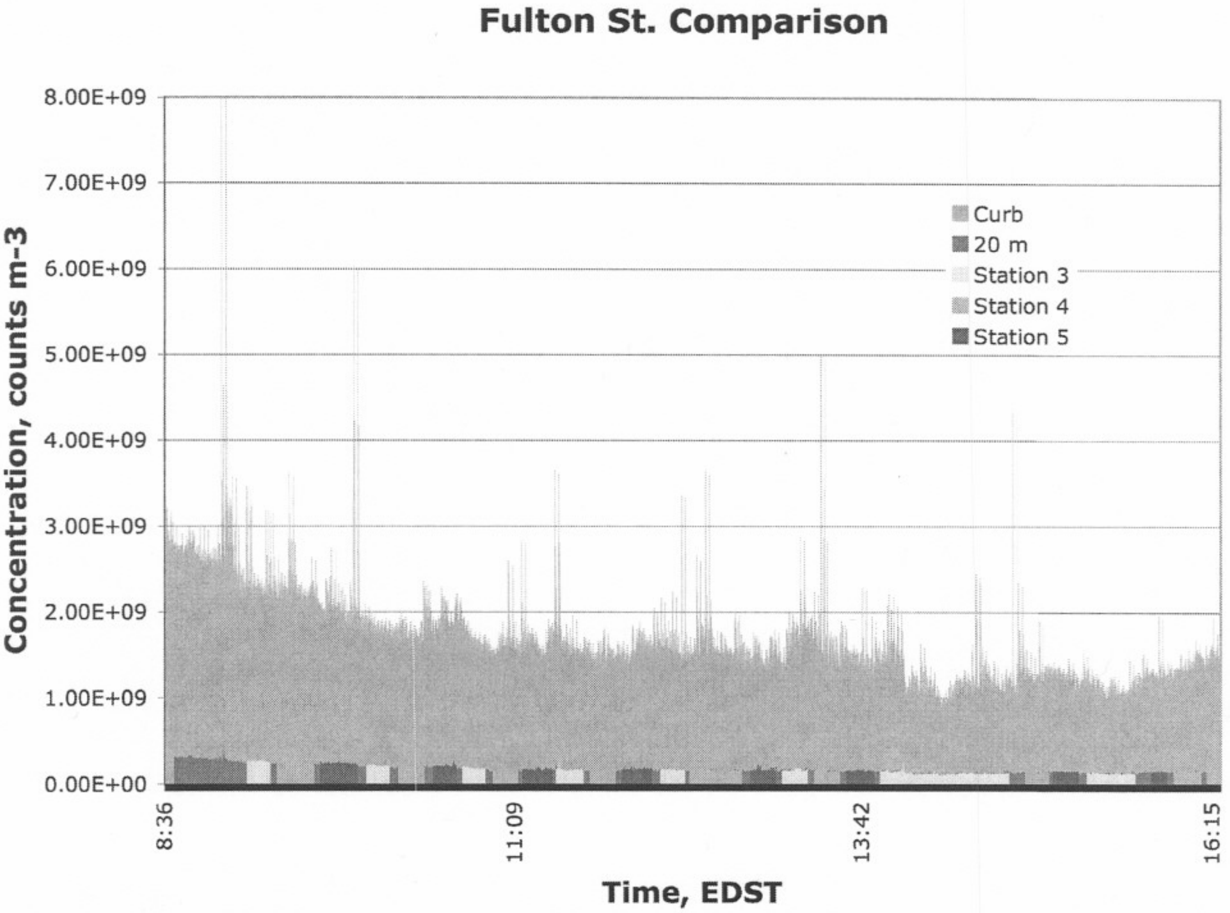


Figure 10. PM2.5 concentration along Fulton St. Baltimore, MD. Curb refers to a stationary monitor remaining at curbside throughout the day, 20 m refers to a stationary monitor 20 from the curb in a vacant lot and stations 3-5 refer to a mobile monitor that was moved among locations in a back alley every 15 min.

Regulatory agencies tend to monitor air pollution in locations that do not correspond to places where people work, play, study and travel and the data collected at official monitoring stations is unlikely to reflect real exposure. If we want to design landscapes with the goal of reducing human exposure to PM. thereby reducing the incidence of asthma and other respiratory diseases, we need to understand the fine-grained behavior of PM in these landscapes.

Second is the effect distance has on reducing the concentration of PM. The old adage, "the solution to pollution is dilution" is certainly true for many atmospheric pollutants in that their concentration decreases as an inverse power of the distance from the source regardless of the contribution of vegetation. If we are interested in reducing the risk of exposure to high PM concentrations, a logical first step would be to separate vulnerable populations of concern such as school children from local sources like roads. If we include buffer strips in designs for schools and sports fields and set back sidewalks from the curb, it becomes logically compelling to vegetate these zones rather than leaving them bare or paved. Our perspective probably should shift from viewing the urban forest as a collection of individual trees to stands whose massed effects will have an impact on their immediate surroundings.

Third, it is clear from the diurnal patterns of [PM] at street level that concentration spikes decay to the same background concentration that existed before the spike. Background concentration is largely a property of the regional air mass and remains essentially unaffected by local conditions. While trees and sophisticated urban design may be able to reduce exposure to transients, it is unrealistic to expect these measures to clean the air beyond what the cleanest ambient air can deliver.

OTHER ACCOMPLISHMENTS

One MS thesis was completed in conjunction with this project. Support for the student (ca. $42 thousand) came from other non-federal sources, so the NUCFAC funds have been leveraged well beyond the required 1:1 match.