AEROSOL DEPOSITION ON PLANT LEAVES

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Abstract. An aerosol generator and wind tunnel system designed for use in aerosol deposition are described. Gross deposition on rough pubescent leaves was nearly seven times greater than on smooth, waxy leaves. Results suggest that aerosol deposition, on a per unit area basis, for single horizontal streamlining leaves is similar to that for arrays of leaves under similar flow conditions. Wind re-entrainment of $PbCl_2$ particles was negligible while 2.54 cm of simulated rainfall was sufficient to remove 85% of recently applied aerosol.

1. Introduction

The primary source of Pb in most communities is from the particulate emissions from automobiles. This Pb is transported by the atmosphere from the highway and deposited on soil and plant surfaces. In this study we examine the deposition of aerosol particulate on plant leaves as well as its removal via wind reentrainment and rain water washing.

The deposition of aerosol particulate on plant leaves is controlled by characteristics of the aerosol (size, chemical composition, cloud density), the leaf surface (roughness, pubescence, moisture, stickiness), and the environment in which the plant lives (relative humidity, wind speed). Once a toxic aerosol is deposited on a leaf surface it may gain entrance into the interior of the plant and be translocated throughout the plant to cause adverse effects on physiological processes within the plant. It is the possibility of physiological plant damage from Pb particulate that formed the impetus for this study. By being able to accurately predict the extent of particle deposition on plant leaves under various conditions and its subsequent removal by the action of wind or rainfall, an estimation of plant dosage can be ascertained for aerosol particulate.

Since the primary objective in the first part of this investigation was to study the gross depositon of an aerosol on plant leaves in a well-defined flow field and not the resulting physiological response, it was proposed that a uranine aerosol (Na salt of 3,4-dehydroxylfluoran) be used in place of Pb aerosol. The primary reason for this was the ease with which uranine can be quantitatively analyzed as opposed to Pb. An initial series of experiments was conducted to demonstrate the validity of this approach. We then compared (1) particle deposition on smooth, waxy leaves with that of rough, pubescent leaves and (2) deposition on single leaves with that on groups or assemblages of leaves. Additional experiments with lead-fumigated plants included (3) wind reentrainment and (4) rain water washing of deposited Pb.

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2. Experimental System

A 0.929 m^2 steel wind tunnel ≈ 7.3 m in length was constructed as a transport system for the deposition studies (Wedding and Stukel, 1976). Air entering the tunnel is passed through an absolute particle filter (99.99% capture efficiency for particles greater than 0.3 μm diameter) before entering the test section. Monodisperse aerosol particles, produced by a vibrating orifice aerosol generator (Berglund and Liu, 1973; Wedding and Sukel, 1974) are carried into the wind tunnel by a stream of dry, filtered air that is passed through a static eliminator (Po 210 source) to remove excess residual particle charge. Air flow within the wind tunnel is then passed through a stairmand disk (Green and Lane, 1957) to increase mixing and homogeneity of particles in the airstream. Consequently the turbulent scale of the air stream is greatly increased. To reduce the large-scale turbulence, the air is first passed through a flow straightening element (grid of 2.54 cm diameter holes) and then through a series of 0.158 cm mesh (0.045 cm diameter wire) grids spaced 2.54 cm apart (Baines and Peterson, 1951). The turbulence scale is thus reduced to nearly isotropic conditions. This is conducive to obtaining a uniform cloud profile during aerosol experiments. Also, the effects of surface characteristics in aerosol deposition can be best determined in a flow regime of this nature where deposition induced by random large-scale fluid perturbations is held to a minimum. The air stream then enters a 1.22 m long Plexiglass test section equipped with access ports at the top and bottom.

Air flow is induced by a blower on the exit end of the wind tunnel, controlled by a damper on the blower, measured by the pressure drop across a calibrated American Society of Mechanical Engineers-standard nozzle, and exhausted through a ventilating hood. The contamination of exhaust air is prevented by two absolute particle filters placed in the exit section of the wind tunnel.

Measurements of particle cloud concentration were taken with an isokinetic sampling probe at different locations in the test section. The cloud concentration of 3.02 μg m^{-3} was uniform throughout the test section (Wedding and Stukel, 1974). All leaf deposition experiments were conducted at a wind speed of 268 cm s^{-1} and an aerosol cloud density of 44.9 μg min^{-1} for the 0.929 m^2 cross-sectional area of the test section. Fumigation periods varied in length from 10 to 35 min. Relative humidity and air temperature varied between 55 to 60% and 24 to 28°C, respectively.

For the wind reentrainment and rain water washing experiments a fumigation chamber was constructed in which the aerial portions of 10 plants could be uniformly fumigated simultaneously. This chamber was lighted from above with fluorescent lamps to maintain normal plant physiological activity and correct daylength during fumigation periods. Fumigation periods of 15 to 20 h were necessary to obtain the desired leaf concentration of 500 to 1000 μg Pb g^{-1} dry weight. $PbCl_2$ aerosol particulate with a diameter of 1.5 to 3.0 μm was used in these experiments. The wind reentrainment experiments were done in the previously described wind tunnel with horizontal trailing leaves at wind velocities of 2.3, 4.8, and 7.0 m s^{-1} for 1 h and the rain water washing with a rain producing module (Chow and Yen, 1974) located at a height of ≈ 3 m above the plants. Rainstorm size was kept constant at 2.54 cm with intensity varying from 2.54 cm h^{-1} to 10.2 cm h^{-1}. Runoff was collected at regular intervals throughout each rain treatment and analyzed for Pb content.

Uranine was analyzed fluorometrically by washing fumigated leaves (or filter paper from the isokinetic sampling probe) with a known amount of deionized water and measuring the concentration of uranine in the wash water with a calibrated Turner fluorometer. Similar preparations of unfumigated leaves were used as blanks in these determinations. Lead was analyzed by the Heavy Metals Analytical Laboratory at the University of illinois, Urbana, using standard atomic absorption techniques for the analysis of plant material.

Leaves of sunflower (*Helianthus annuus* L.) and tulip poplar (*Liriodendron tulipifera* L.) were used in the gross deposition studies. These species were chosen to be representative of plants with large differences in leaf surface characteristics so as to bound the correlation between surface roughness and deposition. Leaves were either fumigated individually or in groups (leaf assemblages). Single leaves were supported at the petiole in a trailing position, parallel to the air flow in the wind tunnel. Leaf assemblages were constructed by placing the petioles of the leaves into small openings of a 'stem' such that the base of the petioles were immersed in water. In this manner, leaf number and leaf area could be varied over a wide range. Leaf area was determined by planimetering outline tracings of individual leaves with a Lasico Polar Planimeter and expressed as the area of one side for each leaf. By rotating the 'stem' during fumigation a reasonable approximation to a tree can be modeled with wind striking the assemblage from all sides. This is not unlike the situation that an isolated tree might experience over time in an urban environment.

For the wind reentrainment and rain water washing experiments, soybean plants (*Glycine max* L.) were used. These were grown from seed for ≈ 5 weeks to a height of ≈ 30 cm in a controlled environment room at which time they were used in the experiments.

3. Results and Discussion

The first experiment examined the similarity of gross deposition on leaves between particles of Pb and those of uranine dye. While it is known that uranine particles with a diameter of 6.77 μm are aerodynamically equivalent to $PbCl_2$ particles with a diameter of 3.36 μm, it was not clear that the deposition of these two aerosols would be the same under identical conditions. To compare the two aerosols, sunflower leaves were used as the deposition surface. The sunflower leaves were placed horizontally within the test section, such that during fumigation they assumed a stable position in the air stream with very little movement. The results of these experiments (Figure 1) show that the aerosol collected by leaves fumigated with uranine was esentially identical to that of leaves fumigated with $PbCl_2$ particles. This confirmed that fumigation with 6.77 μm diameter particles could be successfully substituted for 3.36 μm diameter $PbCl_2$ particles in at least some aerosol deposition experiments. It should be noted, however, that no conclusions on adverse physiological effects should be drawn from the use of particles with aerodynamically equivalent diameters because the ease of entrance of particles into the leaf is dependent on particle size.

The second experiment was designed to test the hypothesis that differences in leaf surface characteristics play a major role in influencing aerosol deposition. Rough pubescent leaves of sunflower were compared to the glaborous leaves of tulip poplar. Single leaves were positioned horizontally in the test chamber and fumigated with uranine particles. It was believed that this orientation would best discriminate between differences in surface characteristics by the following reason. The particles are

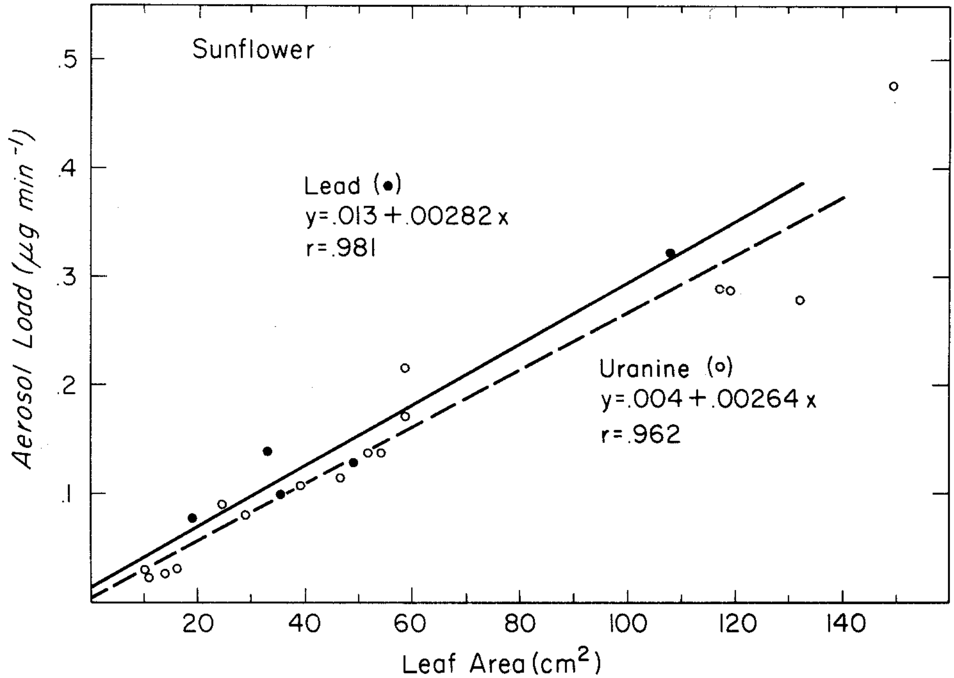

Fig. 1. Comparison in aerosol deposition between $PbCl_2$ particles of 3.36 μm and uranine dye particles of 6.77 μm diameter on single streamlining leaves of sunflower. Aerosol load is the amount of particulate on the leaf after 10 to 35 min of deposition expressed on a per minute basis. Leaf area, determined from outline leaf tracings, is equal to the surface area of one side per leaf.

transported to the deposition surface primarily by turbulent diffusion and under these flow conditions, if a particle attaches to the surface, it has a high probability of remaining (Wedding and Stukel, 1976). Thus, any greater degree of capturing ability exhibited by one species over another would be due essentially to an increased deposition area caused by greater roughness of hairiness. This roughness profile appears most prominently to the particles when the leaf is parallel to the direction of particle trajectory. The deposition rate on the pubescent leaves of sunflower was nearly seven times that of the nonpubescent leaves of tulip poplar. As all other conditions during the fumigation of these two species were the same, it is concluded that the difference in aerosol deposition is due only to differences in leaf surface characteristics. The data appear to conform to a linear relationship as indicated by the regression coefficients.

In the next experiment, the rate of deposition for a group or assemblage of leaves was studied. The results indicate that the deposition rate per unit leaf area for the assemblages was essentially identical to the single trailing leaves, i.e., the rate was

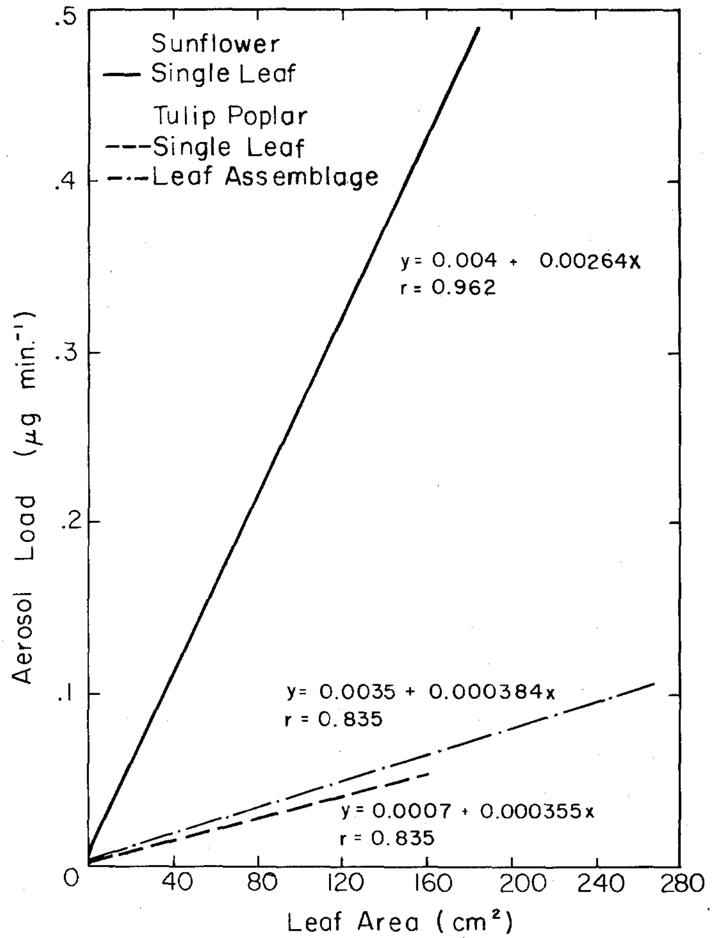

Fig. 2. Deposition of uranine dye particles on single leaves and leaf assemblages of tulip poplar compared with single leaves of sunflower. Aerosol load and leaf area are expressed as in Fig. 1.

linearly related to the total leaf area as shown in Figure 2. The increase in leaf area was achieved by making the 'tree' more and more dense or decreasing the effective flow area between the leaves. As deposition by impaction is negligible for this particle size and flow rate, one might expect the rate of deposition to decrease or level off somewhat as the porosity of the tree approached that of a solid object. This was not the case. Also, the random motion of the leaves flapping violently would cause considerably different flow conditions to prevail than that of the single trailing leaf with little motion. Even though the fluid dynamics are different, the functional form and value of the results are the same.

In our experiments there was no wind reentrainment of deposited $PbCl_2$ aerosol particulate. This was true even at a windspeed of 7 m s^{-1} during which the leaf assumed a fairly violent fluttering action throughout the 1 h reentrainment treatment. The lack of particulate reentrainment was not unexpected from previous theoretical considerations (Wedding and Stukel, 1976).

In the final experiment we examined the effects of simulated rain water washing on removal of deposited $PbCl_2$. We found that (1) 2.54 cm of rain was sufficient to remove 85% of the deposited $PbCl_2$, (2) the amount washed off was independent of intensity over the range of 2.54 cm h^{-1} to 10.2 cm h^{-1}, and (3) no additional $PbCl_2$ could be removed during an additional 2.54 cm of rain. These results were obtained for a recently deposited, relatively insoluble aerosol particulate. The washoff of a more soluble particulate such as sulfate may be more complete with less rainfall. However, it is difficult to predict what the rate of washoff might be in the case of a longer particulate residence on leaf surfaces. Surface chemical reactions might take place over time that would make deposited particulate less vulnerable to washoff through greater insolubility, greater adsorption, or absorption into the leaf.

The results suggest that a dose-response curve can be quantitatively determined for plants growing in an environment where the ambient aerosol cloud concentration is known. The apparent simplicity of the relationship between surface area and deposition suggests that mathematical models for aerosol deposition on plant surfaces via the diffusion process are possible. This is a step toward formulation of a quantitative model to assess the potential damage of toxic aerosol particulate on crop yield.

Acknowledgments

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