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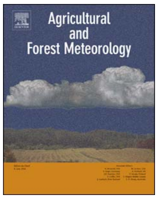

Heavy particle transport in a trellised agricultural canopy during non-row-aligned winds

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ABSTRACT

Agricultural systems are exposed to and influenced by particles of many types (e.g., pathogens, pollen, pests), the concentrations of which are typically highest in the regions immediately surrounding their sources. The intermittent nature of trellised canopies creates an unique canopy architecture that directly affects the shape of particulate plumes and tends to alter their transport patterns in the near-source region. To investigate the behavior of particle plumes near their sources in a trellised canopy, a set of particle release experiments was conducted during a field campaign in an Oregon vineyard in 2013. Specifically, plumes of inert fluorescent microspheres (10–45 μm diameter) were released into the canopy during periods when the mean wind direction was significantly different from the vine-row direction. Plume concentrations were collected at over 100 separate locations in a three-dimensional space < 10 canopy heights downwind of the source during each release period. These plumes were more complex than those released during periods of row-aligned winds. A novel analysis approach using the superposition of two orthogonal Gaussian plume equations was developed to quantitatively assess the behavior of the plumes' shape and its dependence on wind direction and magnitude and on particle release height. Basic plume shape parameters, as determined by integrating the superposed Gaussian equation, varied significantly as a function of the mean wind direction. As the wind direction changed from roughly row-diagonal to directly row-normal, the rate at which the spanwise plume width increased with downwind distance increased by a factor of two. Similarly, the rate at which the plume height increased with downwind distance was higher for row-perpendicular plumes than for row-diagonal plumes. Row-diagonal plumes exhibited a much higher spanwise skewness than did the row-normal plumes, but for all plumes the skewnesses tended towards zero (symmetric) with increasing downwind distance.

1. Introduction

Particle transport in canopies has received considerable research interest in recent years (e.g., Venkatram et al., 2004; Pardyjak et al., 2008; Pan et al., 2014; Miller et al., 2015). Most canopy-based particle transport studies have been done in two types of canopies: urban and quasi-urban canopies, typified by buildings of various heights and spacings and by inhomogeneities like deep street canyons; and vegetative canopies, the majority of which have been relatively dense and essentially horizontally homogeneous. In both canopy types, dispersion patterns have been studied over a large range of length scales. The urban based studies have typically focused on dispersion patterns at length scales much larger than the local building and street scales (e.g., Hanna and Baja, 2009). Dispersion patterns on local scales are often very irregular and more difficult to study due to the complexity of local building and street effects, and therefore, fewer studies have focused on these areas (e.g., Allwine et al., 2002; Belcher, 2005). Similarly, dispersion studies in agricultural or natural vegetative canopies have usually either focused on sub-canopy dispersion in relatively dense, homogenous canopies (e.g., Aylor and Ferrandino, 1989; Gleicher et al., 2014) or on transport at scales much larger than the field scale, wherein in-canopy physics and near-source patterns were of lesser concern (e.g., Brown and Hovmoller, 2002; Spijkerboer et al., 2002; Prussin et al., 2015). More complex plant canopies, with local inhomogeneities, large gaps between plants, or multidimensional trellising systems have received little research attention by comparison.

High-value perennial crops, like grapes, berries, and hops, are typically grown in complex canopies which often have large gaps between plants. Additionally, many perennial crop growers are moving toward the use of trellising systems that structure the canopies for optimal growth and ease of harvest (Robinson et al., 1991; Lauri, 2009). Trellising creates a uniquely structured and heterogeneous architecture

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unlike either urban canopies or homogenous plant canopies. Improved understanding of transport of particulates into and within the plant canopies and the flow physics that dictate that transport will help develop more sustainable crop management practices (Mahaffee et al., 2011). From an ecological standpoint, because particle concentrations (e.g., fungal spores, pesticide sprays, pollen) are typically highest near their source, and are therefore likely to have the greatest impact in that region, resolving their behavior within the canopy and near the source is of great interest (Mahaffee and Stoll, 2016).

In order to investigate the effects that the structured architecture of a trellised canopy has on particle plume behavior near the source, a series of field campaigns was conducted in a commercial vineyard near Monmouth, Oregon where fluorescent microsphere plumes and meteorological characteristics were monitored. These experiments were designed to explore which factors have the largest explanatory power on plume shapes in the near-source and should therefore be emphasized in future modeling studies. Miller et al. (2015) examined particle plumes collected in 2011 during periods when the mean winds were nearly aligned with the vine-row direction. The work here is focused on plumes that were released during periods when the mean wind direction at 5 × the canopy height was significantly different from the vine rows' orientation, i.e., $> 40^\circ$ away from row-parallel (Section 2). Extensive analysis of the meteorological data, including mean statistics, turbulent fluxes, and energy spectra, is reported in Miller et al. (2017). A novel analysis technique that uses the superposition of two Gaussian plume equations was developed (Section 3) and was fit to the concentration data from each plume in order to estimate average plume shape parameters. These parameters were then studied to understand the signature of the canopy architecture on the behavior of the plume (Section 4). This work of understanding the dynamics of the plume behavior is a critical step towards the future development of models that could accurately predict plumes in this type of environment.

2. Field campaign

The specifics of the vineyard architecture as well as extensive statistics on the velocity field, momentum fluxes, turbulent kinetic energy, and turbulent spectra from data collected in the vineyard during the 2013 campaign are detailed in Miller et al. (2017). Here, it is sufficient to say that the vineyard canopy was 2.15 m tall (h) with north-to-south oriented rows spaced at 2.5 m on center (r_s), and that a meteorological tower was placed in the center of an aisle near the middle of a relatively flat vineyard block ($\approx 44^\circ 49' 27.0''$N, $123^\circ 14' 17.0''$W). The tower had six Campbell Scientific CSAT3 sonic anemometers at heights of $z = 10.1$, 5.0, 3.0, 2.0, 1.4, and 0.7 m. Tri-directional wind data, defined as $u_i = \{u_\perp, v_\parallel, w\}$, where $u_\perp$ and $v_\parallel$ were velocity components oriented perpendicular to (x') and parallel to (y') the vine row direction, respectively, were logged throughout the weeks-long campaign. Other meteorological variables that were relevant to the field campaign—like fine-wire thermocouple temperatures (T)—were also logged for use in this and other studies (e.g., Bailey et al., 2016).

2.1. Dispersion experiments

The series of microsphere release events were conducted using violet (UVPMS-BV-1.00, Cospheric LLC), orange (UVPMS-BO-1.00, Cospheric LLC), and yellow/green (UVPMS-BY2-1.00, Cospheric LLC) polyethylene microspheres. Each color had > 90% of spheres within the diameter (d) range of 10–45 μm (Fig. 1). The violet, orange, and yellow/green microspheres had average diameters of 30.9, 34.1, and 32.8 μm, respectively. When the average diameter for each color was determined on a per-mass basis, the average diameters were 33.1, 35.5, and 35.4 μm, respectively. These ranges of d and the microspheres' density (1.005 g/cm^3) corresponded well with the average hydraulic diameter of the spores of multiple common fungal pathogens found in vineyards. This includes *Botrytis cinerea* (d = 8–12 μm, Jarvis, 1977), *Erysiphe necator* (d = 20–36 μm, Braun, 1995), and *Plasmopara viticola* (d = 30–50 μm, Waterhouse, 1973).

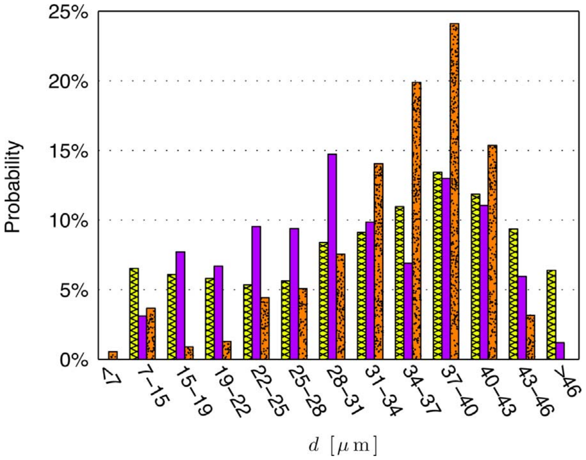

Fig. 1. Histogram of the microsphere diameters (d). The yellow hatched bars, the solid violet bars, and the speckled orange bars represent the yellow, violet, and orange microspheres, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The microspheres were suspended in a 0.05% v/v Tween 20 solution at 0.05 g/ml which was then emitted into the canopy using ultrasonic atomizer nozzles (Sonaer Inc.). Three nozzles were mounted into the canopy at separate individual heights with the nozzle tips pointed downward (Fig. 2). Immediately before each release event syringes were filled with the microspheres and loaded into a syringe pump (Model 22, Harvard Apparatus) which was set to deliver 0.5 ml/min. The violet, orange, and yellow/green microspheres were released during each release event from upper-canopy (H_r = 1.51 m), mid-canopy (H_r = 1.16 m), and lower-canopy (H_r = 0.81 m) heights, respectively

The airborne microsphere concentrations were sampled using rotating arm impaction traps (Miller et al., 2015). The impaction traps' sampling surfaces rotated at 11.7 m/s at individual sampling heights of z = 4.9, 1.9, 1.4, 0.9, and 0.2 m. The sampling heights were chosen based on lessons learned from the 2011 campaign, e.g., a desire for concentration data nearer to the ground. An array of 23 aluminum towers was positioned downwind, east and northeast, of the release location. This resulted in each plume being sampled at 115 separate locations in a three-dimensional (3D) volume at downwind distances between 1.5 and 21 m from the release nozzles (Fig. 3). The asymmetric layout of the towers was designed based on expected mean wind directions from the southwest and the expectation that the channeling of the wind by the vines would create asymmetry in the plumes (Miller et al., 2015, 2017). The ultrasonic nozzles, the impaction traps, and the syringe pump were all controlled using a wireless mesh network using Xbee modules (Digi International Inc.), which allowed for operation from outside the vineyard block.

A total of 12 release events, with three plumes in each, were conducted when $|\delta| > 40^\circ$, where δ was the difference between the above-canopy mean wind direction determined at z = 10 m ($\overline{\mathrm{wd}}$, where the overbar represents a mean taken over the time window of the individual plume release event) and the vine-row direction (Miller et al., 2015, 2017). Each release event was conducted in the afternoon hours when fungal spores are typically transported in the field (Pady and Subbayya, 1970). This resulted in each of the release events having an