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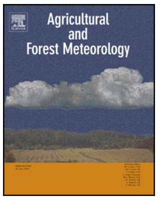

An experimental study of momentum and heavy particle transport in a trellised agricultural canopy

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ABSTRACT

Turbulent particle dispersion in plant canopies plays an important role in many agricultural and forestry ecosystems. Most research on dispersion in plant canopies has focused on dispersal patterns in homogeneous dense canopies and/or on patterns far from the source. To study near-source particle dispersion in a sparse agricultural canopy, a series of point-source particle release events was conducted in a commercial vineyard. Analysis of the wind velocity data indicated that the majority of the flow in the open spaces between the vine rows was channeled parallel to the vine rows regardless of the direction of the mean wind above the canopy. Although this channeling led to significant turning of the mean velocity, profiles of turbulent statistics taken at times when the above-canopy winds were nearly parallel to the vine rows showed similar behavior to canopy flow profiles in previous studies. The particle release events were conducted using fluorescent microspheres with similar physical characteristics to the spores of multiple airborne fungal pathogens of grapes (diameter = 10–45 μm, density = 1.0 g/cm^3). Microspheres were released from two vertical positions within the canopy and monitored using a dense three dimensional impaction trap array in the near-source region (1–5 canopy heights downwind). The shape of the microsphere plumes was strongly impacted by the flow channeling within the canopy. Specifically, the plumes' maximum concentrations were typically channelled down the aisle in which they originated. The spanwise concentration profile also tended to be skewed from the release aisle toward the mean wind direction above the canopy. This was believed to be caused by the wind directional shear created by the difference between the mean wind direction above the canopy and the vine row direction as well as the filtering effects of the plants themselves.

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1. Introduction

Turbulent dispersion in a plant canopy differs from dispersion in the free atmospheric boundary layer (ABL) because of the interplay between the canopy architecture and the local meteorological conditions. Within plant canopies, enhanced turbulent intermittency (Finnigan, 2000) can drastically alter dispersion gradients (Ferrandino, 1993). In addition, the canopy's plant density has a direct impact on the canopy-atmosphere interaction and the characteristics of dispersion (Bailey et al., 2014).

Most previous studies of momentum transport and particle dispersion in plant canopies have focused on dense canopies (e.g., Aylor and Ferrandino, 1989; Dwyer et al., 1997; Finnigan, 2000; Thomas and Foken, 2007; Yue et al., 2007; Su et al., 1998) or on forest clearings and edge flows (e.g., Yang et al., 2006; Dupont and Brunet, 2008; Detto et al., 2008; Cassiani et al., 2008). Significantly fewer experimental (e.g., Weiss and Allen, 1976; Verhoef et al., 1997; Novak et al., 2000; Böhm et al., 2013) and numerical (e.g., Su et al., 2008; Huang et al., 2009; Bailey and Stoll, 2013; Bailey et al., 2014) studies have focused on sparse canopies where the canopy had discontinuities at length scales on the order of the canopy height. These few primarily focused on momentum transport with the experimental studies often using wind tunnel or water channel canopy models with a single type of canopy architecture (e.g., arrays of cylinders, see: Raupach et al., 1980; Judd et al., 1996; Novak et al., 2000; Poggi et al., 2004; Böhm et al., 2013). One exception to this is the experiment of Patton et al. (2011) which reported measurements of momentum transport in a sparse walnut orchard. In the numerical studies, the analysis typically treated the canopy as horizontally homogenous (e.g., Dupont and Brunet, 2008; Huang et al., 2009).

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The majority of the experimental field studies that have examined particle transport in plant canopies have been performed in dense canopies (e.g., Raynor et al., 1974; Aylor and Ferrandino, 1989; Gleicher et al., 2014). In addition to a focus on dense canopies, the information about particle plume spread dynamics has often been limited by low particle sampling densities that are only along a single arc or plane. The studies have used their data for applications including the validation of Lagrangian particle models (Aylor et al., 2001), average canopy vertical particle flux modeling (Chamecki et al., 2012), and maximum concentration tracking (Hanna and Baja, 2009). A few studies have used three-dimensional sampling arrays but have focused on more qualitative spread evaluation (Raynor et al., 1974) or on model validation and not specifically on the three-dimensional plume shape (Gleicher et al., 2014). These studies were also performed in dense canopies and did not use dense enough arrays to characterize the plume shape in the near-source region. None of these studies examined both momentum and particle transport in a sparse plant canopy.

Exceptions to the focus on dense canopies include Novak et al. (2000) and Poggi et al. (2004) which investigated the effect of canopy density on momentum transport. These studies did not investigate the density effects on particle transport and were still performed on relatively homogenous canopies. Considerably fewer studies have focused on sparse non-homogenous canopies (e.g., Weiss and Allen, 1976; Bailey and Stoll, 2013; Bailey et al., 2014). Bailey and Stoll (2013) and Bailey et al. (2014) used numerical simulations to study transport within two-dimensional row oriented canopies when the wind was blowing orthogonally to the row direction. They found that momentum and particle transport in these canopies are functions of canopy architecture. In particular for momentum transport, the horizontal heterogeneity created by the row structure had an impact on second- and third-order momentum statistics, resulted in significant dispersive fluxes in the lower part of the canopy, and preferentially located coherent structure events. When examining massless non-depositing particles, they found that canopy heterogeneity increased vertical particle fluxes, decreased residence time of particles in the canopy, and decreased the persistence of particle motions.

The focus of this study was on sparse perennial agricultural canopies organized into rows. These types of canopies are typified by trellised canopies of *Vitis vinifera* (grape vineyards). Grape vineyard canopies are approximately two-dimensional with large open spaces creating discontinuities at length scales on the order of the canopy height. This geometry directly impacts the mean velocity field resulting in a rotation of the mean wind towards the row direction (Weiss and Allen, 1976) with direct consequences for vine biophysiology (Tarara et al., 2005). Grape vineyard canopies were of interest due to their direct economic impact (USDA, 2013), the increased use of trellised canopies in a variety of crops (Talaie et al., 2011), and because they share many characteristics with other canopies of importance in agricultural and urban applications including wind breaks (Patton et al., 1998; Raupach et al., 2001; Bouvet et al., 2006; Speckart and Pardyjak, 2014) and urban street canyons (Belcher, 2005; Klein et al., 2007; Addepalli and Pardyjak, 2013).

We hypothesized that the sparse geometry of grape vineyard canopies and other canopies with similar characteristics, through its influence on the mean wind and local fluxes, would play a central role in determining particle dispersion dynamics within and above the canopy. Specifically, we expected that the canopy would affect the mean advection direction, the rate of plume spread, and the shape of the spanwise profile of the plume. To test this hypothesis, a field campaign (Section 2) was conducted in a vineyard in Western Oregon. Particle transport was studied through a series of controlled particle release experiments using polyethylene microspheres with a size range similar to spores of multiple fungal grape pathogens. A high density, three-dimensional array of samplers was used to collect the microspheres allowing for the plume shape to be investigated in detail. The momentum transport statistics within the vineyard (Section 3) and the results of the release events were used to elucidate the canopy's influence on particle dispersion (Section 4).

2. Field campaign

The field study was performed during September and October 2011 in a commercial vineyard in the Willamette valley near Monmouth, Oregon at ≈44° 49′ 28.0″ N, 123° 14′ 17.0″ W. The vineyard is a relatively flat site of ≈43 hectares with vine rows oriented to within ±2° of true north-to-south. The experiments were conducted in the southeast portion of the field where the plant growth was the most homogeneous. The wind at this location came primarily from the north and southwesterly directions providing a maximum upstream fetch (>350 m) composed of nearly continuous trellised vines. The terrain had a west-to-east downslope of ≈2.4% and a south to north down slope of ≈0.8%.

Throughout the experiment, a meteorological tower (Fig. 1) with four Campbell Scientific CSAT3 sonic anemometers was placed in the aisle between two rows of vines with the anemometers pointing to true north. The anemometers were placed at heights of 5, 2.9, 1.8, and 0.8 m. The lowest two anemometers were placed such that the bottom and top of the canopy immediately around the tower were within their sampling volumes. Additionally, the sampling volume of the 1.8 m anemometer was aligned with the canopy's top-most trellis wire. The anemometers collected tri-directional wind data [streamwise (u), spanwise (v), and vertical (w)] and the sonic temperature (T) at each height. The meteorological data were recorded 24 h/day at 20 Hz using a Campbell Scientific CR5000 Datalogger.

The surrounding canopy had an average height (h) of 1.90 m with local variation from one plant to the next (Fig. 1). The vine rows were spaced (r_s) at 2.49 m on center and were ≈0.46 m wide leaving aisles of ≈2 m wide. The leaf area density (*LAD*, one-sided area of leaves per canopy volume) profile (Fig. 2) was determined by randomly selecting ten vines within the sample area, counting the number of shoots per vine, and randomly removing a shoot from the left and right of the trunk. Leaves from each shoot were removed and digitally assessed for leaf area using Assess Image Analysis Software (The American Phytopathological Society, St. Paul, MN). The leaf area index (*LAI*, area of leaves per area of ground) was determined based on the same data and was found to be 1.4 for the whole vineyard block. When an individual row of vines was considered with the ground directly beneath it the *LAI* was 7.5. Similar *LAI* values were reported in Johnson et al. (2003) for vineyards of comparable architecture.

2.1. Meteorological data processing

The data from the meteorological tower was partitioned into independent continuous 30-min periods. This period length was sufficient to ensure convergence of flux statistics while maintaining flow steadiness. The mean wind direction for each period at each anemometer height was determined and periods with southerly winds between 165° and 195° (coming from behind the tower) at any height were excluded from further analysis. A three-dimensional coordinate rotation was then applied to the wind velocity data of the $z = 5$ m anemometer for each period so that only u had an average >0 (see Pardyjak and Cuerva, 2007). The wind velocity data for the lower three anemometers were rotated following the rotation determined at the 5 m anemometer.

Standard relevant statistics including the average streamwise velocity at $z = 5$ m ($\overline{u}$) and the mean wind direction at that height

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