



Short communication

A case study of air quality above an urban roof top vegetable farm

Zheming Tong ^a, Thomas H. Whitlow ^{b,*}, Andrew Landers ^c, Benjamin Flanner ^d^a Center for Green Buildings and Cities, Graduate School of Design, Harvard University, Cambridge, MA 02138, USA^b Section of Horticulture, School of Integrative Plant Science, Cornell University, Room 23 Plant Science Building, Ithaca, NY 14853, USA^c Department of Entomology, NYAES, 312 Barton Lab Cornell University Geneva, NY 14456, USA^d Brooklyn Grange Flagship Farm 37–18 Northern Blvd. Long Island City, NY 11101, USA

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ABSTRACT

The effect of elevation and rooftop configuration on local air quality was investigated at the Brooklyn Grange rooftop farm during a short-term observational campaign. Using multiple particle counters and sonic anemometers deployed along vertical gradients, we found that PM_{2.5} concentration decayed with height above the street. Samples adjacent to the street had the highest average PM_{2.5} concentration and frequent stochastic spikes above background. Rooftop observations 26 m above ground showed 7–33% reductions in average PM_{2.5} concentration compared with the curbside and had far fewer spikes. A relationship between the vertical extinction rate of PM_{2.5} and atmospheric stability was found whereby less unstable atmosphere and greater wind shear led to greater PM_{2.5} extinction due to damped vertical motion of air.

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1. Introduction

Over the past 2 decades, green roofs have gained popularity as a means to enhance urban sustainability by restoring ecosystem services. Among the many goals are increasing energy efficiency, reducing the urban heat island, prolonging the roof membrane, detaining storm water runoff, filtering particulate matter from the air and producing local food for city dwellers (Niachou et al., 2001; Getter and Rowe, 2006; Rosenzweig et al., 2006a, 2006b; Oberndorfer et al., 2007; Czemuil Berndtsson, 2010; Rowe, 2011; Whittinghill and Rowe, 2012; Koski, 2013). All of these goals are worthy and appealing, but air filtration and food production may be somewhat at odds with each other. For example, while removing PM would improve air quality, food safety could be compromised by heavy metal contamination of rooftop soil and vegetable produce. Removal of particulate air pollution depends on the characteristics of the rooftop boundary layer, the roughness of the vegetation canopy and the position of the roof relative to pollution sources. Because roofs are above local street traffic, rooftop vegetation might be expected to play a more limited role in removing traffic-related pollution.

While several studies have investigated the air quality aspect of urban green roofs, none have studied a rooftop vegetable farm. A study in Manchester, UK found that green roofs received between 0.41 and 3.21 g m⁻² year⁻¹ of PM₁₀ (Speak et al., 2012). Using a dry deposition model, Yang et al. estimated that 1676 kg of air pollutants were removed per year by 198.8 ha of green roofs in Chicago (Yang et al., 2008). Currie and Bass calculated that 7870 kg of pollutants were removed annually by green roofs in Toronto using the UFORE model (Currie and Bass, 2008). The latter two estimates are based on dry deposition velocity values from the literature for PM₁₀ that were scaled up to an entire city. While this simplification is a useful starting point, these studies cannot account for the effect of complex aerodynamics at the building scale. In addition, dry deposition velocity reports in the literature vary by an order of magnitude. Building scale field studies are needed to evaluate the air quality on building roofs, the potential for green roofs to contribute to improving air quality, and the likelihood that vegetables grown on rooftops pose a greater health risk than those grown at ground level.

Here, we report findings of an exploratory field campaign to quantify the vertical distribution of PM_{2.5} along an elevation gradient next to a building with a rooftop farm. We focused on PM_{2.5} as a useful proxy for pollutants that could deposit to vegetables, and many epidemiological studies have shown that increased PM_{2.5} exposure leads to various adverse health effects

* Corresponding author.

E-mail address: thw2@cornell.edu (T.H. Whitlow).

(McConnell et al., 2006; HEI, 2013). Using multiple particle counters and sonic anemometers, this approach achieved high spatial and temporal resolution of PM_{2.5} concentration in discrete particle size classes and corresponding wind data. To our knowledge, no site-specific study has investigated the spatiotemporal pattern of PM_{2.5} concentrations on a green roof located near a major urban thoroughfare. This study demonstrates the importance of collecting empirical data that is necessary for landscape-scale, as opposed to city or regional scale models.

2. Methodology

2.1. Sampling location

Brooklyn Grange Rooftop Farm in New York City is the world's largest urban rooftop farm, with 40,000 square feet devoted to vegetable and herb production. The farm is located on the roof of a seven-story building next to Northern Blvd., a Principal Arterial road with 36,794 AADT (Annual Average Daily Traffic). Additional details about the sampling location are shown in Table 1.

2.2. Experimental approach and instrumentation

A brief description of the experimental approach and instrumentation are presented here. Additional details are available in our previous studies (Whitlow et al., 2011; Tong et al., 2015). Portable monitoring instruments were used to conduct an intensive monitoring campaign during one-week period, lasting about 10 h each day during daylight hours and capturing both morning and evening rush hours. PM_{2.5} was measured using 3 Grimm Aerosol Spectrometers (Model 1.108) equipped with isokinetic probes to reduce the effects of variable wind speed. 15 size classes were monitored between 0.3 and 20 µm every 6 s, approximating a human resting inhalation rate. We approximated fine particulate matter (PM_{2.5}) as the sum of all sizes from 0.3 µm to 3.0 µm, and particle counts were converted to mass by assuming that the particles are spherical and using the conversion factor 1.4 g/cm³ (Armbruster et al., 1984; Murakami et al., 2005). Three particle counters were deployed for three sampling locations (roadside, 3rd floor, rooftop) as shown in Fig. 1. Four 3-D Gill sonic anemometers were placed vertically on a mast on the roof to measure the instantaneous wind speed and direction at 1 Hz. These data were used to generate vertical wind profiles.

2.3. Data analysis

2.3.1. Temporal variation

Koniographs, analogous to hydrographs used by hydrologists, were used to show fine scale temporal variation in concentration at the 6-s sampling frequency of the aerosol spectrometers (Whitlow et al., 2011; Tong et al., 2015). This sampling rate approximates the human inhalation rate, hence exposure to short term concentration spikes.

Table 1

Coordinate of Brooklyn Grange Rooftop Farm, sampling date, and sampling elevation.

	Longitude	Latitude	Date	Sampling elevation
Brooklyn Grange Rooftop Farm	40.752	-73.926	June 19/20/21, 2012	Street-level, 13 m, roof 26 m

2.3.2. Return period

A return period estimates the magnitude of the highest concentration occurring during a given period. Recognizing that air pollution events are stochastic over time, resembling flood events, we employed the Gumbel Method to calculate the return period of PM_{2.5} events of any observed magnitude during each day's set of observations (Gumbel, 1941). In our usage here, the time scale is in minutes.

2.3.3. Atmospheric stability

To ensure that the stability indicated by wind profile at the rooftop is consistent with observations at a local meteorology station, a meteorological processor (AERMET) developed by the EPA was employed to compute the Monin–Obukhov length L , which provides a measure of stability (Venkatram, 1980; USEPA, 2004; Foken, 2006; Simpson et al., 2007). Hourly surface data were obtained from the nearest weather station at LaGuardia Airport 4.3 km NE of the site, and upper air data were obtained at Brookhaven, NY.

3. Results and discussion

The high resolution of the 6-s sampling frequency shows the nearly instantaneous stochastic variation of PM_{2.5} concentration in a road-building environment (Fig. 2). Sampling location at the street level displayed the most variable PM_{2.5} concentration, showing frequent spikes above background. Because the spectrometers cannot detect particles <0.3 µm, concentration spikes include secondary particles and particles re-suspended from the road surface. The sampling station on the 3rd floor showed less frequent concentration spikes in contrast with the street level. Although many concentration spikes at the street level were closely correlated with spikes at the 3rd floor, non-synchronous spikes were also observed at the 3rd floor on June 20 (Fig. 2). Observations on the roof top were consistently less variable than at either of the other sampling locations, indicating that PM_{2.5} exposure on the rooftop is much less than at street level in terms of both daily average and frequency of stochastic spikes.

Fig. 3 shows the return period plot for each of the three sampling days. Return period plots based on the three vertical sampling stations illustrate the importance of elevation in determining exposure risk. For all events, elevated sampling locations had lower PM_{2.5} concentrations and fewer spikes per sampling period. For example, on June 20, the 10 min event was ca. 20 µg/m³ on the street but only ca. 13 µg/m³ on the third floor and 11 µg/m³ on the roof. Street level concentrations ≥30 µg/m³ (nearly 4 times the street-level average) recur every 100 min.

Table 2 shows the average daily concentration and standard deviation of PM_{2.5} based on roughly 5000 sampling points. Decay curves normalized to the street-level concentration show the attenuation of PM_{2.5} concentration from the street level to the rooftop (Fig. 4). The steepest decay was observed on June 19 (33% reduction) compared with a 7% reduction on the June 20.

The extinction rate of PM_{2.5} correlates with atmospheric stability. Using meteorological data from the nearest National Weather Service observation station (LaGuardia airport, 4.3 km NE) we determined that the range of atmospheric instability observed during our campaign occurred 72% of the time from June–Aug, 2012, suggesting that our results are a reasonable representation of conditions in the summer growing season. The Monin–Obukhov lengths, L , fall between -17 and -123 m, indicating that unstable to very unstable conditions predominate (Fig. 5). The more gradual velocity gradient on June 19 indicates less instability, wind shear, and damped vertical air motion, all of which effectively decouple the roof from street-level pollution. In

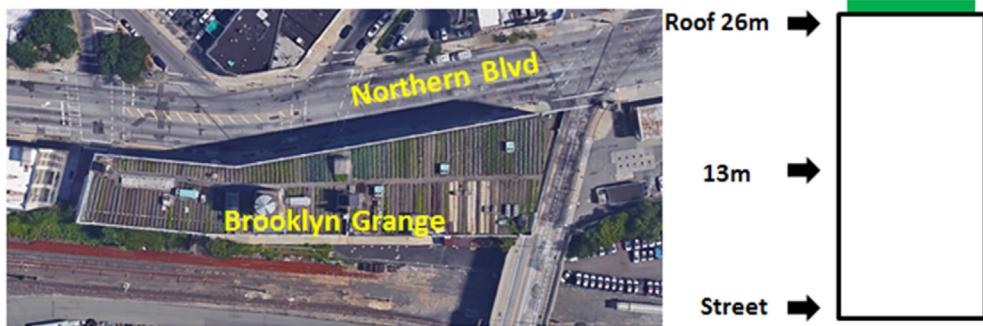


Fig. 1. Satellite image of Brooklyn Grange Rooftop Farm and an elevation view of the 3 sampling locations.

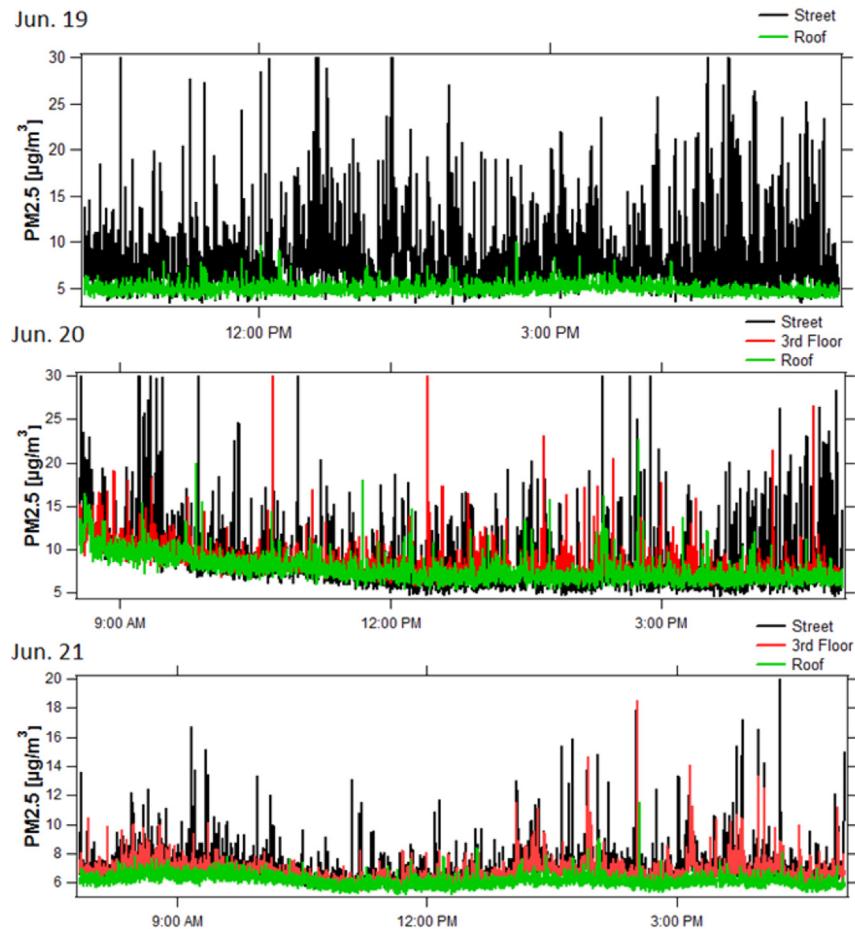


Fig. 2. PM_{2.5} Konigraphs of three sampling days at 6 s sampling resolution at Brooklyn Grange. Concentrations at the Street level, 3rd floor, and roof top are overlaid in the same figure. The 3rd floor sampling point was not used on Jun 19 due to logistical problems.

comparison, on June 20, stronger vertical air movement reduced wind shear and prevented a sharp increase of wind speed with height.

Importantly, despite the variation in overall velocity profiles, the velocity profiles below 1.5 m remain nearly constant with time, ambient wind, and stability conditions (Fig. 5). We infer from this that the perimeter wall, not the crop canopy, governs aerodynamics near the roof. While the crop canopy is rougher than a roof surface without vegetation, relatively large bluff objects like the 1.5 m perimeter wall create a boundary layer with small scale eddies that overrides the effect of vegetation canopy. In addition, the major component of PM_{2.5} we are interested in consists of particles

between 0.1 and 2.0 μm in diameter. This is the range where deposition velocity is lowest, suggesting that the roles of Brownian diffusion, impaction and interception in governing concentration in the air are limited compared to the role of dispersion (Sehmel, 1980; Seinfeld and Pandis, 2006), regardless of the presence of rooftop vegetation. Although a nearby roof lacking vegetation was not available for comparison, we suggest that rooftop aerodynamics and dispersion override the effect of particle deposition to the crop canopy.

Fig. 6 presents mass the proportions of each particle size measured from 0.3–0.4 μm to 2–3 μm . The proportion of larger particles (e.g. 1.6–3 μm) at street level exceeds those at roof level

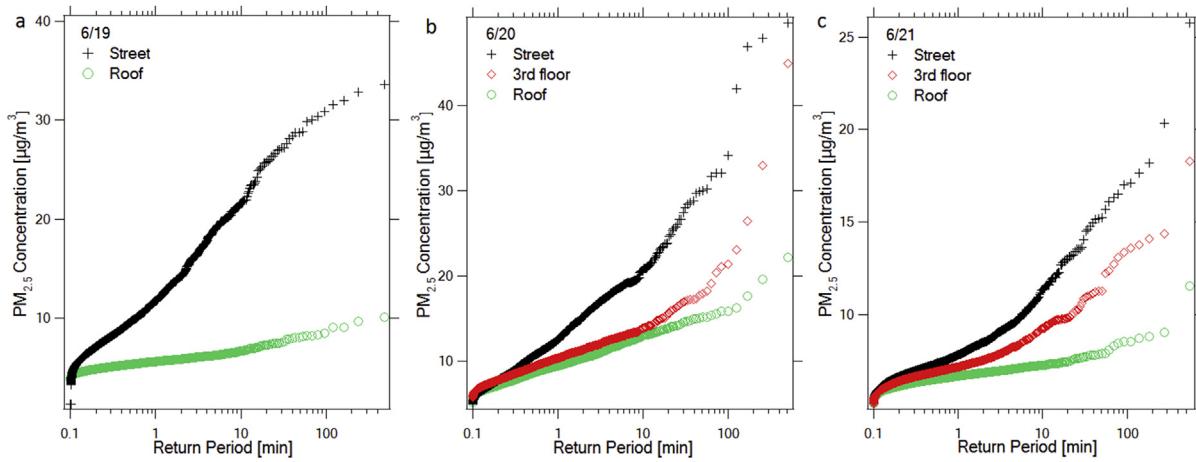


Fig. 3. Return period plot for Jun. 19, 20, and 21 in 2012. The measurement point at the 3rd floor was not available on Jun 19 due to logistical problems.

Table 2

Average PM_{2.5} concentrations and standard deviation (in parentheses) at each measurement station.

	Street	3rd floor	Roof	Regression equation	R ²
6/19/2012	8.09 (± 3.42) µg/m ³	N/A	4.98 (± 0.56) µg/m ³	C = 0.40exp(-0.068z) + 0.61	0.94
6/20/2012	7.78 (± 2.85) µg/m ³	7.64 (± 1.42) µg/m ³	7.03 (± 1.00) µg/m ³	C = 0.10exp(-0.053z) + 0.90	0.73
6/21/2012	7.04 (± 1.10) µg/m ³	6.74 (± 0.77) µg/m ³	6.10 (± 0.36) µg/m ³	C = 0.14exp(-0.060z) + 0.87	0.83

while the finest fraction (0.3–0.4 µm) is higher on the roof. This finding is likely due to wear products that were re-suspended from the pavement by vehicle-induced turbulence at street level (Wang and Zhang, 2009; Tong et al., 2012; Tong and Zhang, 2015).

4. Conclusions

While we cannot make definitive statements about PM_{2.5} concentrations on a rooftop farm under all meteorological conditions, this brief field campaign nevertheless has several important findings. Street level samples had the most variable PM_{2.5} concentration, showing frequent stochastic spikes above background. Observations from the Brooklyn Grange farm (26 m above ground) showed a 7–33% reduction in average PM_{2.5} concentration and far fewer stochastic spikes. Less unstable atmospheric conditions with correspondingly greater wind shear caused a PM_{2.5} concentration to decline more sharply with elevation due to damped vertical

motion of air. We also observed a 1.5 m thick turbulent boundary layer near the roof generated by the perimeter wall that exists regardless of atmospheric stability and ambient wind. Combined with the low deposition velocity of the major mass fraction of PM_{2.5} particles, we speculate that the influence of rooftop structures on aerodynamics and dispersion override the effect of deposition to

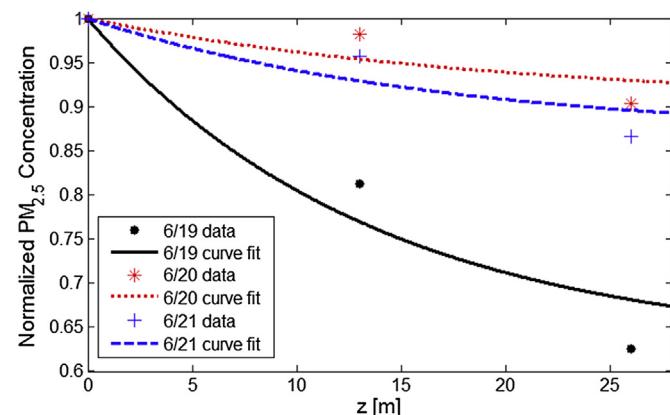


Fig. 4. Normalized PM_{2.5} decay curve of three sampling days as a function of vertical elevation. The concentration on third floor was not measured. An average between the street level and rooftop concentration was used for curve fitting purpose.

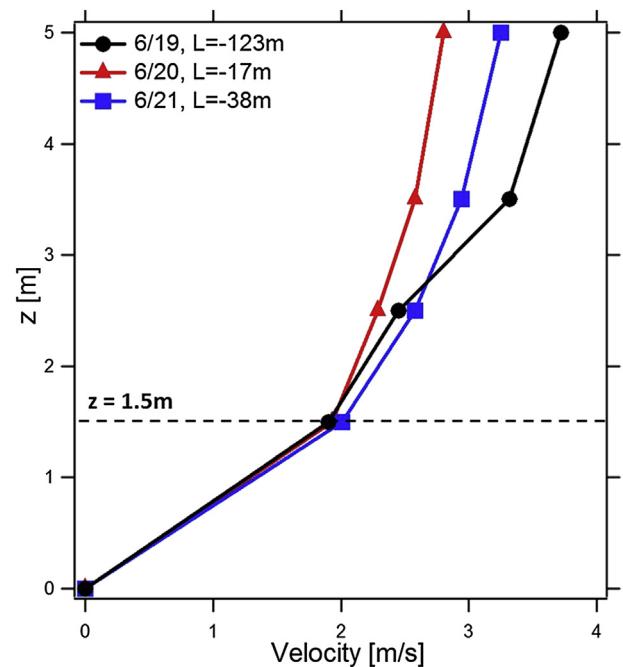


Fig. 5. Vertical wind velocity profile of three sampling days as a function of vertical elevation on the rooftop. Monin–Obukhov lengths L computed by AERMET are shown in the legend. On all 3 days, the velocity profiles are undistinguishable below 1.5 m of the roof. 1.5 m is the height of the first vertically placed anemometer and roughly the height of the perimeter wall above the roof surface.

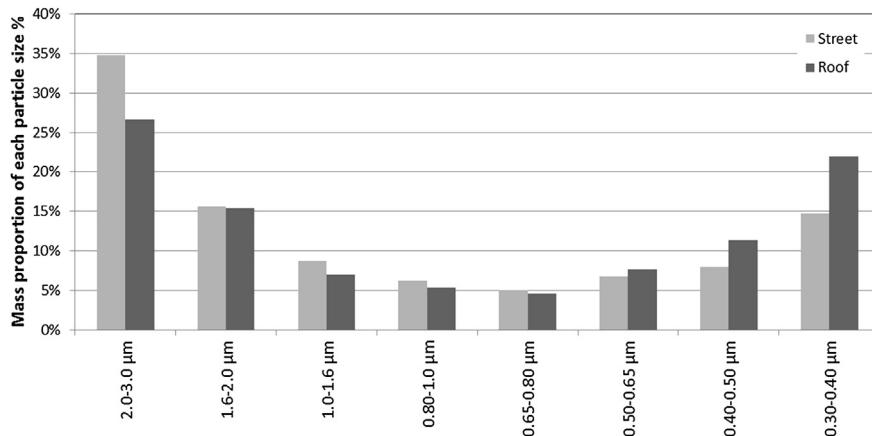


Fig. 6. Mass proportion of each particle size class in bar chart at rooftop and street level.

vegetation in determining local air quality. The proportion of larger particles (e.g. 1.6–3 μm) at street level was considerably greater than that at roof level, likely due to the resuspension of vehicular wear products from the road surface.

In sum, three important ideas emerge from this study that are relevant to both urban farming practices and our understanding of ecosystem services attributed to green roofs. We state these as the following hypotheses: (1) Human exposure to PM_{2.5} arising from street level traffic will be lower on a roof than at street level; (2) Vegetables grown on rooftops will receive a reduced pollution load, including heavy metals, than crops grown in the ground near roads; (3) Plants on green roofs are likely to remove less air pollution than ground level vegetation due to the effect of building elevation on the vertical gradient of PM_{2.5}.

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