PM_{10} Emission Factors for Harvest and Tillage of Row Crops

Teresa Cassel, Krystyna Trzepla-Nabaglo, Robert Flocchini
Crocker Nuclear Lab, University of California at Davis, Davis, CA 95616
tacassel@ucdavis.edu, Nabaglo@crocker.ucdavis.edu, rgflocchini@ucdavis.edu

ABSTRACT

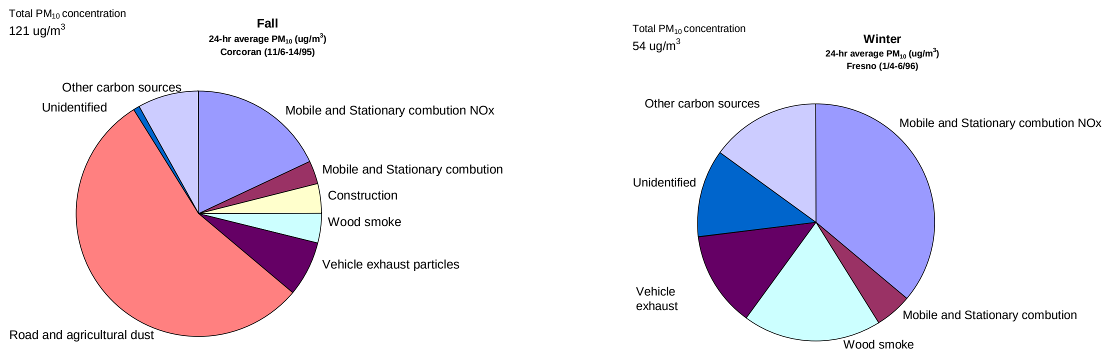
The San Joaquin Valley of California is in non-attainment of National Ambient Air Quality Standards for PM_{10}. The occurrence of 24-hour exceedences during periods of intense agricultural activity in the post-harvest months of October and November, as well as the composition of ambient PM_{10} at that time, indicates the importance of row crop agriculture in the region's air quality. Measured PM_{10} emission factors for harvest and land preparation operations in several row crops are presented. Emission factors are confirmed with real-time remote particle detection techniques (lidar) and further parameterized with measurement uncertainties and replicate measurements. The effect of soil moisture and relative humidity as they relate to seasonality and crop specificity are shown to be significant in determining PM_{10} emission factors for similar activities under varying field conditions.

INTRODUCTION

The United States Environmental Protection Agency has designated the San Joaquin Valley (SJV) a serious non-attainment area for PM_{10}, particulate matter with an aerodynamic diameter less than 10 micrometers. This means the valley exceeds the National Ambient Air Quality Standards (24-hour average of 150 $\mu g/m^3$ and annual average of 50 $\mu g/m^3$) for PM_{10} and required local policy is being drafted in an attempt to meet them. PM_{10} bypass the body's defense mechanisms and penetrate into the respiratory system. These particles have been linked to death by cardiac and respiratory disease.

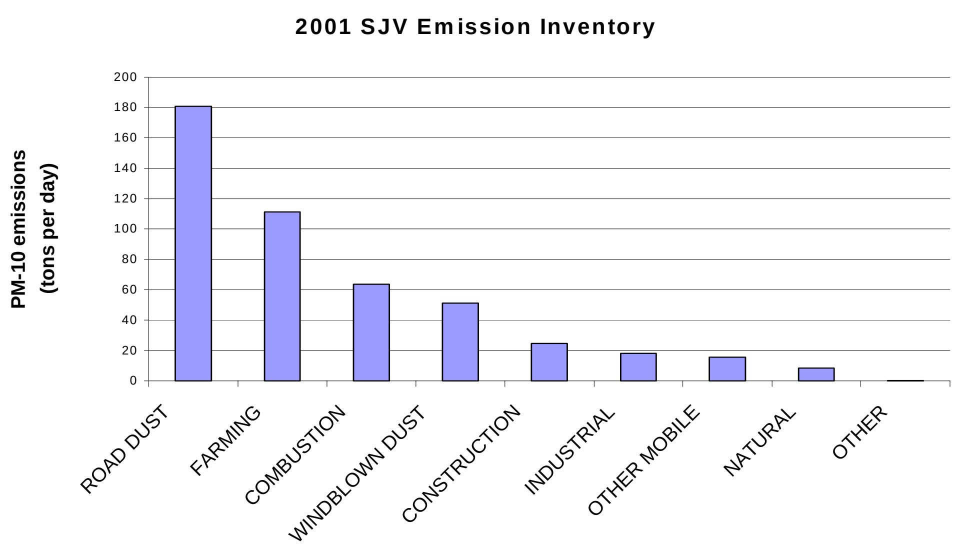
The seasonal variations in measured concentrations and compositions of PM_{10} in the valley are illustrated in Figure 1, obtained from data collected during the 1995 Integrated Monitoring Study (Magliano, et al.,1999). The relatively higher PM_{10} concentration measured in Corcoran in early November is typical of the late fall season when PM_{10} exceedences are most common in the valley (Figure 1a). Source contribution profiles are based on the ionic and elemental composition of the particulate matter sample collected. The SJV is one of the most productive agricultural regions in the United States. In 1997 agriculture contributed $26.8 billion to the state's economy (Johnston and Carter, 2000). The dominance of fugitive dust from mobile and agricultural sources in the fall leads to the hypothesis that agricultural sources may make a significant contribution to the non-attainment status of the SJV. Figure 1b shows a typical winter source contribution profile in which secondary particulate matter dominates and fugitive dust sources are negligible in the rainy season.

Figure 1. Source contributions to ambient PM_{10} in the San Joaquin Valley in the fall and winter. From Magliano, et al., 1999.



Emission inventories are compiled by the California Air Resources Board (CARB) to quantify the relative contributions of all possible sources of PM_{10} in a specific region to the annual average PM_{10} concentration in that region. Emission inventories are also used by the Districts, the San Joaquin Valley Air Pollution Control District (SJVAPCD) in the case of the SJV, to plan for attainment of the air quality standards. The SJVAPCD is currently preparing a PM_{10} attainment plan, which must include strategies to lower the annual average PM_{10} concentration in the valley by 5% per year. According to the 2001 emission inventory, farming operations are the second most significant source of PM_{10} in the valley (Figure 2).

Figure 2. PM_{10} emission inventory for the San Joaquin Valley, 2001. (adopted from download at www.arb.ca.gov)



An accurate PM_{10} emission inventory is critical to the development of an effective PM_{10} attainment plan. Until recently, PM_{10} emissions from all farming operations were estimated using a single emission factor, which was derived from studies of unpaved road emissions (U.S.E.P.A. ,1995). This paper presents measured emission factors for a variety of farming operations. To investigate the applicability of these emission factors to the wide range of farming practices employed in California, specific tillage procedures such as discing, floating, and land planning were compared for different crops. Emission factor response to relative humidity and soil moisture was also investigated to allow for assignment of available emission factors to crops that were not measured based on the seasonal timing of crop harvest.

METHODS

All field measurements were made under actual field conditions. While sampling was coordinated with cooperative growers, special treatment of the fields to accommodate PM_{10} sampling was not requested. A combination of upwind/downwind source isolation and vertical profiling methods were used to quantify PM_{10} emission factors, as described in Holmén et al. (2000). Measurements were made between 1996 and 2000 by comparable methods using one upwind and at least one downwind vertical profile. Aerosol samples and meteorological data were collected at the heights indicated in Table 1. While PM measurements made at the top of the towers were actually between 8.5 and 10 m above ground level, they are all referred to by the nominal height of 9 m. When possible, two or three towers were used in different locations downwind of the source to better characterize the plume and provide analysis of sampling uncertainty. Soil samples were collected from the region of the field over which the tractor traveled each time either the operation or the soil conditions changed.

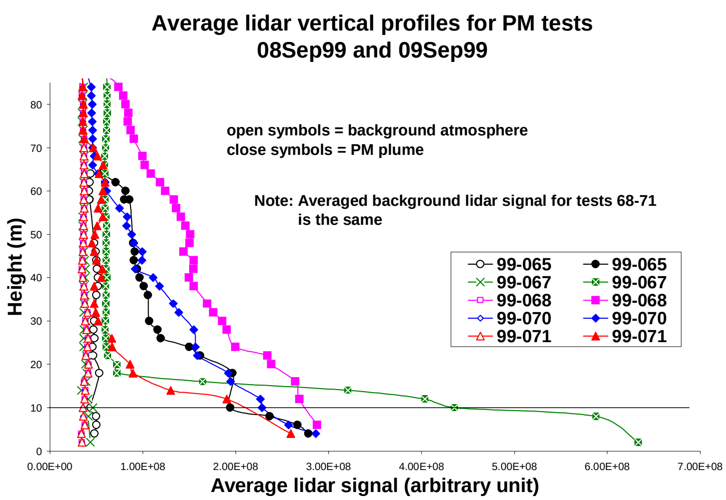
Table 1. Description of equipment used to measure PM_{10} emission factors and heights of deployment during research conducted between 1996 and 2000.

Measured variable	Year	Height (m)
PM_{10} concentration	96-99	1, 3, 9
	2000	1, 3, 5, 9
Air temperature	96-00	0.5, 1, 2, 4, 7.5
Wind direction	1996	2
	97-00	4
Relative humidity	96-00	2
CNL elastic lidar (1064 nm)	97-00	2D vertical scans from ground level to 100 m

As described in Holmén et al. (2000), a lidar instrument was utilized in most of the field tests conducted between 1997 and 2000 to provide detailed information about plumes generated during these agricultural operations, specifically their heights, shapes and dynamics. In elastic lidar, the light scattered back towards the lidar instrument from molecules and particles in the atmosphere is collected by a telescope and measured with a photodetector. The detector signal is digitized and analyzed to create a real-time detailed image of aerosol concentrations within the scanned area.

Qualitative measurements of relative PM backscatter were obtained by collecting vertical two-dimensional (2D) scans. These measurements were analyzed to obtain vertical profiles of lidar data by averaging the lidar signal at 2 m height intervals over a specific range interval corresponding to the location of the PM tower, plus/minus 10 m on each site of the tower. For example, if the PM tower was located 470 m from the lidar, the lidar vertical scans with plumes between 460 and 480 m were averaged. The background vertical profiles were obtained using the same procedure but from the scans collected during breaks in operation. Figure 3 shows some averaged lidar vertical profiles corresponding to PM tests during land planning operation. The height (on the Y-axis) where PM plume and background profiles intersect is defined in these measurements as the top of the plume.

Figure 3. Lidar vertical profiles of plumes determined by averaging lidar signal detected at the PM sampler location in height intervals of 2 meters (closed symbols). Background vertical profiles (open symbols) were collected when the plumes were not generated due to breaks in agricultural operations. The horizontal line at 10 m represents the highest sampler location.



PM_{10} emission factors for agricultural operations were quantified on the basis of the area of land worked. Three different methods – the line, block and logarithmic profile models – were used to fit the PM_{10} vertical concentration profiles as described previously (Holmén et al. 2000). A fourth model, the box model was used to describe the PM_{10} flux in cases of uniform downwind vertical concentration profiles. Measurements of PM_{10} mass concentration above MDL at a minimum of three sampling heights were required for calculation of emission factors. The choice of the appropriate model for each downwind concentration profile type was based, in part, on the plume height calculated from simultaneous lidar data collected during some of the field tests.

For each model, a horizontal PM_{10} flux was calculated as the product of the net (i.e., downwind – upwind) PM_{10} concentration [mg m^{-3}], *C(h)*, and the average horizontal wind speed [m s^{-1}], *U(h)*, at ten equally spaced height intervals [m], *dh*, between z_o and the top of the plume, H. The plume height was defined by the intersection of the downwind profiles with the average upwind concentration. The flux was integrated over the height of the plume using Simpson's Rule, and normalized by the time of the test, *t*, the upwind width of soil worked during the test period, w, and the angle between the measured wind direction and the direction perpendicular to the field edge, θ, to compute the PM_{10} emission factor [mg m^{-2}].

Equation (1) $$E = \int_{z_0}^{H} \frac{U(h)C(h)t\cos\theta}{w} dh$$

where

E = emission factor

C(h) = net PM10 concentration

U(h) = average horizontal wind speed

z_0 = surface roughness

H = height of the top of the plume

w = width of the field and

θ = angle between the measured wind direction and perpendicular to the field edge.

t = time of test

Uncertainties in the calculated emission factors were estimated using error propagation techniques (Coleman and Steele,1989) for the line, block and logarithmic fit models. The PM_{10} measurement uncertainties and the test period wind speed standard deviation at each measurement height were used to estimate the uncertainty in the horizontal flux at each of the ten model heights.

RESULTS AND DISCUSSION

Valid measurements of PM_{10} concentrations and meteorological parameters made between 1996 and 2000 produced 135 calculated emission factors for agricultural operations in row crops in the San Joaquin Valley. Data presented in Table 2 are compiled by commodity for select land preparation operations only. Emission factors for land preparation operations are more dependent on seasonality and resulting soil moisture than crop specificity, though the timing of some operations is based on the previous crop such that crop and season are not independent variables.

One example of seasonal and crop dependent differences in emission factors is the discing operation. Forty four measurements of PM_{10} emission factors were made on fields previously planted to cotton, garbanzos, melons, tomatoes, and wheat. When the fields were disked in November and December, following cotton, soil moisture was significantly higher (13%) than in June through September, following the other crops. One notable exception was when discing followed melons, a crop that adds moisture to the soil, for which average soil moisture was 11%.

Two very similar land preparation operations, land planning and floating, had essentially indistinguishable PM_{10} emission factors that appear to be independent of crop, with one interesting exception. In these experiments, land planning was preformed using a steel implement with a single, adjustable bucket and floating was done with a wood framed implement with two or three metal blades that scraped the surface flat. As can be seen in Table 2, floating and land planning conducted under similar conditions of soil moisture yield similar PM_{10} emission factors. This is generally true regardless of the previous crop on the field. The one exception noted in this study was a single measurement of PM_{10} emission factor for floating following melons, when the soil moisture was 11% and the emission factor was only 119 mg/m^2. It seems likely that the high soil moisture in this case accounts for the unusually low emission factor for melons, but additional testing is necessary to demonstrate this effect conclusively.

Table 2. Average PM_{10} emission factors and emission factor uncertainties for specific agricultural operations. Average soil moisture and relative humidity data show relationship between these variables and PM_{10} emission factors.

Source	Emission factor (mg/m^2)	Factor Uncertainty (mg/m^2)	Standard deviation (mg/m^2)	Number of tests	Relative Humidity (%)	Soil moisture (%)	Month of operation
Discing							
cotton	78	6	42	14	59	13	Nov/Dec
garbonzos	313	14	402	2	51	6	July
melon	380	24	278	5	55	11	Aug
tomatoes	545	35	284	10	40	4	Jul/Aug/Sep
wheat	1375	91	881	13	43	3	June/July
Floating							
melon	119	8	0	1	53	11	Aug
tomatoes	2322	110	0	1	40	2	Sep
wheat	1569	145	1277	15	40	3	July
Land Planing							
garbonzos	1704	98	1042	7	34	2	Sep
tomatoes	1229	128	1318	7	42	3	Sep

The dependence of measured PM_{10} emission factors on the type and timing of agricultural operations (Table 2) is supported by the available lidar data. Plume heights and shapes, estimated from averaged lidar vertical profiles, are affected by micrometeorological conditions that vary seasonally. For example, plume heights measured during discing operations in summer (June, July) exceeded 80 m while in winter they were below 50 m. Plume shapes are also less uniformly logarithmic in vertical dispersion (measured as lidar signal intensity with height) in summer than in winter. So plumes are larger in both extent (height) and intensity at those heights in summer as compared to winter. Field tests during which these observations were made correspond to average emission factors for the same season and operation of approximately 1380 mg/m^2 and 65 mg/m^2 for summer and winter, respectively.

Table 3. Average PM_{10} emission factors and emission factor uncertainties for harvest operations. Differences in harvest emission factors may be due to crop specific operational differences or seasonally defined variables such as soil moisture.

Source	Emission factor (mg/m^2)	Factor Uncertainty (mg/m^2)	Standard deviation (mg/m^2)	Number of tests	Relative Humidity (%)	Soil moisture (%)	Month of operation
Cotton harvest							
picking	107	13	87	3	62	15	Oct/Nov
stalk cutting	42	7	37	4	57	12	Nov/Dec
Wheat harvest							
harvest	665	40	441	16	29	3	Jun/July
Tomato harvest							
picking	785	48	195	4	41	9	Jul/Sept

While PM_{10} emission inventories are not currently temporally resolved (they are computed on an annual basis), a review of the timing of specific operations may indicate the importance of agriculturally derived PM_{10} emissions to regional exceedence of PM_{10} concentration standards. For example, late fall exceedences are not likely due to tomato or wheat harvest operations although they have fairly high emission factors, since they only occur during summer months (Table 3). Conversely, floating and land planning operations may make substantial contributions to regional non-attainment status as they are generally preformed in the late fall (Table 2). These observations indicate that revisiting crop calendar development may be beneficial to determine more specifically when the various land preparation operations are conducted following different crops.

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KEYWORDS

Emission Inventories
PM
Area Sources
Agriculture