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Conservation tillage reduces PM_{10} emissions in dairy forage rotations

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Abstract

The San Joaquin Valley (SJV) is a United States Environmental Protection Agency (USEPA) serious non-attainment area for PM_{10}, particulate matter with an aerodynamic diameter $<10\,\mu m$. At certain times of the year, PM_{10} is composed mostly of soil-derived material. The correspondence of air quality violations with intense tillage activities and PM_{10} composition has focused attention on row crop agriculture as a potential major contributor to PM_{10}. This two-year study compared conservation (CT) and standard tillage (ST) systems in dairy forage production to determine if, and to what extent, CT can reduce agricultural PM_{10}. Vertical profiling methods were used to calculate PM_{10} emission factors for both systems at two farm locations.

Test results showed CT reduced PM_{10} emissions by about 85% on both farms in spring 2004 and by 52% on one farm to 93% on another farm in spring 2005. PM_{10} reductions were mainly due to the fewer number of tillage operations in CT systems (zero or one operation compared to three to six in ST) and the higher soil water contents at which CT operations can be performed.

Aside from soil moisture, degree of soil pulverization, characterized in the second year of this study by weighted mean ped diameter (WMPD) also proved to be an important determinant of PM_{10} emissions. The ST second disking always had a higher PM_{10} emission factor than the first disking despite any change in soil water content. The WMPD decreased 39% between the two diskings.

Large discrepancies between PM_{10} emission factors measured in this study and those used for regulatory purposes in California emphasize the continued need to refine monitoring strategies under varying field conditions to improve accuracy of emission factors and to understand how soil and cropping management affect dust production.

Keywords: PM_{10}; Emission factors; Conservation tillage; Soil water content; Weighted mean ped diameter

1. Introduction

The United States Environmental Protection Agency (USEPA) has designated the San Joaquin Valley (SJV) as a serious non-attainment area for PM_{10}. This means the SJV exceeds the National Ambient Air Quality Standards (24-h average of $150\,\mu g\,m^{-3}$ and annual average of $50\,\mu g\,m^{-3}$) for

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PM_{10}, and the state is required to submit a State Implementation Plan (SIP) for the purpose of permitting and monitoring PM_{10} sources and to establish deadlines for attainment. PM_{10} violations are a public concern for two reasons: (1) PM_{10} can bypass the body's interception/impaction mechanisms (i.e., nasal mucus/hairs, curvature of head airways) and penetrate into the tracheobronchial and pulmonary regions of the lungs. Short-term exposure to PM_{10} has been associated with decreased lung function, cardiac arrhythmia, heart attacks and premature death (USEPA, 2004). (2) Failure to reach PM_{10} attainment can result in loss of federal highway funds for the state, payment of mandatory offsets for new or modified PM_{10} sources which can raise the cost of business, and loss of state control of the regulatory process (USEPA, 1990).

According to the California Air Resources Board (CARB) Almanac Emission Projection Data (2005), an annual average of 89% (293 mg day^{-1}) of all PM_{10} in the SJV air basin comes from area-wide sources (i.e., fuel combustion, farming operations, paved and unpaved road dust, fugitive windblown dust, and waste burning and disposal). The other 11% comes from stationary (i.e., power plants, refineries and manufacturing facilities) and mobile (i.e., on- and off-road vehicles) sources. Of the area-wide sources, CARB estimates PM_{10} from farming operations, paved/unpaved roads and windblown dust make up 66% of the total, followed by PM_{10} from managed burning and disposal (26%). Magliano et al. (1999) found similar results using chemical mass balance modeling and on-site PM_{10} measurements at Corcoran and Fresno, CA monitoring stations to determine spatial and temporal variations in PM_{10}. In the fall, when PM_{10} violations often occur, soil material was the largest PM_{10} contributor, averaging 60% of the mass; secondary ammonium nitrates were the next largest (15–20%).

Though it is very difficult to differentiate among PM_{10} from an agricultural field, a construction site, or an unpaved road, the magnitude of SJV agriculture and the timing of PM_{10} violations suggest much of the PM_{10} is from agriculture. The evidence is the following: (1) SJV is California's leading agricultural producing region, with five of its counties—Fresno, Kern, Tulare, Merced and Stanislaus—ranking among the state's top 10 agricultural producing counties. In 2001, out of the \$27.6 billion gross cash income from agricultural production in California, >\$12 billion came from these five counties (CDFA, 2002). To maintain such high productivity, SJV farmers intensely rotate crops (two to three per season). Mitchell et al. (2001) estimated that standard tillage (ST) production systems typically use 9–11 separate tillage operations to prepare the land for each crop. (2) About 45% of the land in the SJV is under agricultural production. In Merced County, the areal extent is 93%. (3) Most of the land preparation is done in the spring (March to May) and in the fall (October to November). This directly corresponds to PM_{10} violations in the SJV (Fig. 1). (4) Though reductions in winter soil-derived PM_{10} have been attributed to cooling of the soil surface, decreased air temperature and increased relative humidity, winter also is a time of fewer tillage activities.

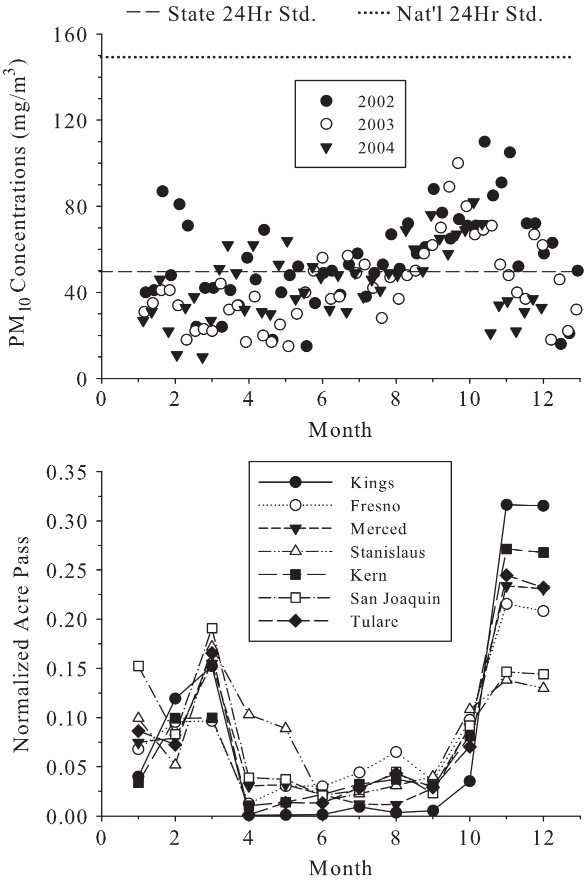

Fig. 1. Bimodal similarities between seasonal PM_{10} levels (Visalia, CA, sampling station) and agricultural land preparation profiles by county in the San Joaquin Valley (Francis, 1997). Normalized monthly acre pass values for each county were determined by summing the total number of monthly acre passes for each crop in a particular county and then dividing it by the county's annual sum of acre passes.

Growing federal concerns over agriculture's contribution to poor air quality in the SJV has put pressure on the San Joaquin Valley Unified Air Pollution Control District (SJVUAPCD) to adopt farm management practices that mitigate PM_{10} emissions. Recently, the SJVUAPCD has recognized conservation tillage (CT) as a viable option for reducing agricultural PM_{10} by decreasing the amount of tillage needed for crop production (NRCS and AIR, 2004). Though CT can be strictly defined as a production system where 30% or more of the soil surface is covered with residue (Reeder, 2000), the major difference between CT and ST is that CT eliminates pre-plant tillage such as plowing, ripping, disking and chiseling. Reduced tillage not only promotes better air quality, but also helps to reduce equipment and labor costs, promote the formation of soil organic matter (SOM) (Reicosky and Lindstrom, 1995), and helps maintain soil micro- and macro-channels important for water infiltration (Ashraf et al., 1999).

Although a reduction of PM_{10} emissions by reducing pre-plant tillage operations seems obvious, few studies have actually quantified the magnitude difference in PM_{10} emissions between CT and ST systems under similar conditions. Previous work (Baker et al., 2005) showed that CT reduces in-the-field dust production by about 66% in a cotton–tomato rotation. This paper expands on that work to test the hypothesis that CT reduces PM_{10} emissions by reducing tillage operations. We also tested the hypothesis that soil water content and soil aggregate size (i.e., weighted mean ped diameter (WMPD)) play major roles in determining PM_{10} emissions. This study used vertical profiling methods similar to those currently used by CARB to develop emission inventories for agricultural operations (Holmen et al., 2001a, b; Flocchini and James, 2001).

2. Materials and methods

2.1. Sampling sites

All field measurements were made during spring 2004 and 2005 on two dairy forage farms: Sweet Haven Dairy, Burrell (Fresno County), CA, and Barcellos Farms, Tipton (Tulare County), CA. Forty-acre comparison plots were set up at each site to measure tillage generated PM_{10} from ST and CT systems. Cropping rotations were mixed forage [wheat (*Triticum aestivum* L.), triticale (× *Triticosecale*), oats (*Avena sativa*)] to corn (*Zea mays* L.). Soil surface textures at Sweet Haven Dairy and Barcellos Farms were fine sandy loam (Chino and Traver fine sandy loam) and loam (Tagus loam), respectively. Specific information recorded at the time of sampling included soil conditions (soil water content and WMPD), wind speed and direction, humidity, air temperature, implement types and dimensions, number of implement passes per test, operation speed, compass direction of operation and distance of operation from PM_{10} sampling tower.

2.2. Meteorological measurements

Wind speed, wind direction, humidity and air temperature data were recorded every minute at the downwind vertical profiling tower using a HOBO weather station (Onset Corp., MA). Air temperature and humidity were measured at a 2 m height, and wind speed and direction were measured at 1 and 3 m in 2004 and 1, 3.4, 6.1 and 11 m heights in 2005. Vertical profiles of wind speed (1 and 3 m in 2004; 1, 3.4, 6.1 and 11 m in 2005) and direction (only 3 and 3.4 m) were used to calculate PM_{10} emission fluxes.

2.3. PM_{10} sampling

PM_{10} measurements were made using one upwind and one downwind vertical profiling tower placed in arrays similar to those described in Holmen et al. (2001a, b). Interagency Monitoring of Protected Visual Environments (IMPROVE) aerosol samplers (Eldred et al., 1990) were used to collect PM_{10} on pre-weighed 25-mm stretched Teflon filters. USEPA-approved Sierra Anderson inlets (Model 246b) produced the 10 μm size cut, and flow regulators operated at 16.7 lpm were identical to those of IMPROVE samplers. Samplers were placed at 1, 3.7, 6.2 and 9 m heights in 2004 and 1, 3.4, 6.1 and 11 m heights in 2005 on the downwind tower and at a 3 m height on the upwind tower. In 2004, samplings for each operation were done in sets of two or three, depending on conditions, with the downwind tower remaining stationary and the tractor moving farther upwind with each subsequent test (distance range: 15.5–69.5 m). In 2005, this approach was modified to where the downwind tower was moved whenever possible after each test so the distance between the tractor and tower was fixed. Sampling times averaged 40 min and were taken when the wind vane showed wind direction was $\leqslant 45^\circ$ from perpendicular to the direction of tractor travel.

2.4. Emission factor calculations

Once PM_{10} plume concentrations were determined by subtracting upwind from downwind pre- and post-treatment masses, a plume profile was drawn by plotting height vs. PM_{10} concentration. As in Holmen et al. (2001a), four different functional models—line, natural logarithmic, block and box profile models—were used to fit the vertical PM_{10} concentration profiles. However, unlike Holmen et al. (2001a), analysis of LIDAR data was not used to choose the appropriate model to fit each profile. Instead, the following criteria were used:

(1) Line or natural logarithmic models were used for PM_{10} profiles where concentrations consistently decreased with an increase in height. Additional selection between the two models was based on the highest coefficient of determination (r^2) values from regression analyses.

(2) Block models were used for PM_{10} profiles where concentrations exhibited zigzag patterns with an increase in height. Similar to Holmen et al. (2001a), the block fit assumed PM_{10} concentrations were constant from 1 m to the ground and linear from 1 to 3 m, 3 to 5 m and 5 to 9 m. Above 9 m, the concentration profile was extrapolated linearly using the 5–9 m line until the line intersected the average upwind PM_{10} concentration. If the 9 m PM_{10} concentration was greater the 5 m concentration, the line model was used since the block model would have given unrealistic plume heights.

(3) Box models were used for profiles where PM_{10} concentrations were uniform with height. The box model essentially transformed the measured PM_{10} and wind speed profiles to a uniform profile based on values collected at the 1 m sampler, and defined a plume height, H_{box}. H_{box} was determined by taking each line-fit integrated mass fluxes for all the profiles where the box model was not an appropriate fit and equating them to the product: (net 1 m PM_{10} concentration $\times$ 1 m wind speed $\times$ h_{box}, where h_{box} represents the defined plume height for each individual test) (Fig. 2). Each h_{box} was empirically adjusted to achieve a 'box' that produced the same integrated PM_{10} mass flux to those measured using the functional models. All h_{box} where then averaged to calculate H_{box}. The H_{box} for our data set was 6.5 m.

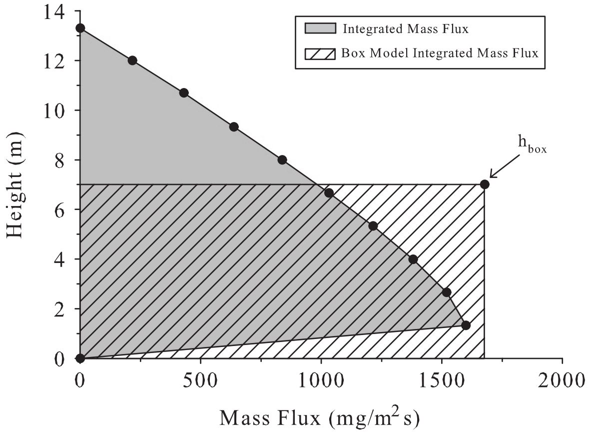

Fig. 2. Example of the box model. The gray area represents the integrated mass flux for a particular test in which a natural logarithmic function was used to describe the plume profile. The cross-hatched area is the box model for this test. Its area is equal in size to the gray area; however its integrated mass flux is calculated by multiplying the test's net 1 m PM_{10} concentration $\times$ 1 m wind speed $\times$ h_{box} (the defined plume height). Since h_{box} is unknown, it must be empirically adjusted until the two areas of the graph are equal.

For each model except the box, a horizontal PM_{10} flux was calculated as the product of the net (i.e., downwind minus upwind) PM_{10} concentration, $C(h)$, and the average horizontal wind speed (m s^{-1}), $U(h)$, at 10 equally spaced height intervals (m), dh, between z_0 (height at which wind speed is zero) and the top of the plume, H. The flux was integrated over the height of the plume and normalized by the duration 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 (E) (mg m^{-2}):

$$E = \int_{z_0}^{H} \frac{U(h)C(h)t\cos\theta}{w}\,\mathrm{d}h \qquad (1)$$

Uncertainties in the calculated emission factors (Tables 2 and 3) were estimated using error propagation techniques (Coleman and Steele, 1989) for the line, block and logarithmic fit models. As in Holmen et al. (2001b), Appendix A, each calculated emission factor uncertainty (EFU) mathematically incorporates PM_{10} measurement uncertainties and test period wind speed standard deviations at each of the 10 modeled height intervals, as well as, standard deviations in the cosine of the wind direction. Errors in the duration of the test and operation distance are assumed to be small and are ignored.

2.5. Soil moisture and weighted mean ped diameter (WMPD)

In 2004, at least two soil samples (0–15 cm depths) were taken prior to each test to determine gravimetric water content (GWC). In 2005, samples were split into 5 cm increments to measure soil moisture as a function of depth. After collection, each sample was pre-weighed, oven-dried at 105 °C for 24–48 h and then weighed again (Gardner et al., 1991). In 2005, WMPD measurements were added to explore relationships between PM_{10} emissions and soil aggregate size. For WMPD, three samples per plot were taken at 0–20 cm depths prior to tests using a method similar to one described by Chepil (1962). All samples were oven-dried at 60 °C to a constant weight. WMPD was determined by sieving the samples for 5.5 min on a Ro Tap (W.S. Tyler, Inc., Mentor, OH) shaker (Van de Graaff, 1978). Six 20 cm diameter sieves with square openings of 31.5, 16, 8, 4, 2 and 1 mm, plus a pan collected seven size fractions. The WMPD was calculated as:

$$\mathrm{WMPD} = \sum_{i=1}^{n} x_i w_i \qquad (2)$$

where x_i is the midpoint of each size interval (in mm); w_i is the proportion of the total mass on a particular sieve (also called mean weight-diameter, Kemper and Chepil, 1965).

2.6. Emission factor confidence ratings

Each calculated emission factor was assigned an overall test rating based on four qualifiers similar to those found in Holmen et al. (2001b). The purpose was to provide a summary of the level of uncertainty within the calculations. The test ratings range from “A” (lowest uncertainty) to “H” (highest uncertainty). Each test rating starts with grade “A”, which was reduced in accordance with the following factors: (1) if the upwind concentration was higher than any of the downwind concentrations, the letter grade was reduced one level (A and B, B and C, etc.) for each downwind concentration exceeded. If only the 9 m concentration was exceeded, no reductions are made (Qup); (2) the wind direction deviated >45° from ideal (i.e., perpendicular to tractor direction), the letter grade was reduced one level (Qwd); (3) if the standard deviation of a test wind direction was >25°, the letter grade was reduced one level (Qwd SD); (4) relative emission factor uncertainty was >20% (based on error propagation), the letter grade was reduced one level. Each qualifier is described in Table 1.

Table 1
Emission factor confidence ratings summary

Qualifier	Criteria	Scale
Qup A–E, upwind concentration	Number of downwind concentrations below the upwind concentration. If only the 9 m downwind concentration is below the upwind, the test rating is “A” under the assumption the plume is below the 9 m height	$A = 0$ dw$<uw$, or only 9 m$<uw$ $B = 1$ dw$<uw$ $C = 2$ dw$<uw$ $D = 3$ dw$<uw$ $E = 4$ dw$<uw$
Qwd>45°, wind direction vs. ideal	If the test wind direction varies by greater than 45° from the ideal wind direction. *Note*: best wind direction is 90° to downwind edge of sampling array	Reduce letter rating assigned at Qup by one level (e.g., A→B, B→C)
Qwd SD>25°, wind direction uncertainty	If the standard deviation of a test wind direction >25°	Reduce letter rating by one level (e.g., A→B)
EFU>20%, relative emission factor uncertainty	(Emission factor uncertainty[a]/emission factor) >20%	Reduce letter rating by one level (e.g., A→B)
TOT, total test grade	Overall confidence in calculated emission factor as represented by a letter grade	A = best H = worst

[a] For emission factor uncertainty calculations, see Appendix A in Holmen et al. (2001b).

3. Results and discussion

3.1. Calculated PM_{10} emission factors

The calculated PM_{10} emission factors and uncertainties for all tillage operations at each dairy are shown in Tables 2 and 3. All model calculations (i.e., line, log, block and box) for each PM_{10} emission factor are also shown for the purposes of comparison. The bold values indicate the model selected to calculate emission factor values. As mentioned earlier, model selection was based on plume shape and r^2 values. Tables 2 and 3 also show a summation (TOT) of the test ratings for each test. The final test grade (i.e., A through H) is an indicator of the level of confidence that should be placed on a calculated PM_{10} emission factor; A = best and H = worst. For determining the effects of CT on PM_{10} emissions, only tests given an A or B grade were used to calculate emission factor averages. Operation averages were then summed up to give the total PM_{10} emitted per system (i.e., CT and ST).

3.2. Reductions in PM_{10} emissions: CT vs. ST

In 2004, averaged test results showed CT reduced PM_{10} emission by 86% at Sweet Haven Dairy and 85% at Barcellos Farms. In 2005, PM_{10} was reduced by 52% and 93%, respectively. This, of course, was due in part to CTs ability to prepare fields for planting with, at most, one tillage operation, while ST required three to six. CT was also performed under higher soil water contents, which have been shown to be an important factor in dust reductions (see section below). Baker et al. (2005) found CT treatments produced up to 66% less PM_4 (particulate matter with an aerodynamic diameter $<4\,\mu m$) than ST treatments due primarily to the reduced number of field operations, especially in bed preparation and in-season cultivation. They also found soil water content to be negatively correlated to PM_4 production ($r^2 = 0.65$).

3.3. Effects of soil on PM_{10} emission factors

Less PM_{10} was produced at higher water contents due to the increased cohesive forces between soil particles (Hillel, 1998). Fig. 3 shows the relationship between calculated PM_{10} emission factors (only tests given an A or B grade) and GWC at each dairy. Similar to Holmen et al. (2001b) and Baker et al. (2005), there was an inverse relationship between GWC and PM_{10} ($r^2 = 0.23$ at Sweet Haven Dairy and $r^2 = 0.21$ at Barcellos Farms). This has been the general tend in other PM studies. Cowherd et al. (1974) found the quantity of dust emissions from agricultural tilling to be proportional to the inverse square of the surface soil moisture (0–10 cm depth). Clausnitzer and Singer (2000) found PM_4 emissions from various tillage operations increased exponentially below a soil water content of 6–7% for a clay loam; about half the GWC held in a clay loam (bulk density $\approx 1.33\,g\,cm^{-3}$) at -1.5 MPa (i.e., permanent wilting point). Of course, this 'threshold' water content range depends on texture and is not a fixed value (Neumann et al., 2006).

Conversely, Cuscino et al. (1981) failed to find significant correlations between soil moisture and total dust (TD), particulates $<100\,\mu m$ aerodynamic diameter. They suggested the existence of a threshold moisture level below which emission magnitude is no longer a function of soil water content. Chepil (1956) found similar results for soils subjected to wind shear forces (i.e., wind erosion). For a given energy input level (related to wind speed), there was a threshold moisture below which soil movement, or soil wind erodibility, ceased to increase. This threshold moisture level corresponded to about one-third the water content held by a soil at -1.5 MPa, regardless of texture. At higher water contents, soil erodibility decreased slowly at first, then more rapidly with each successive increment of water added, reaching zero, on average, at about the -1.5 MPa water content level.

3.4. Effects of WMPD on PM_{10} emission factors

Soil WMPD samples were taken prior to each operation in 2005. Though most previous studies show a strong link between soil water content and PM_{10} emissions, little work has been done on the effects of soil aggregation (as measured by WMPD) and PM_{10} emissions. Tillage operations alter soil structure by reducing the mean aggregate size of the soil in preparation for bed formation and planting. Breaking down soil aggregates makes soil easier to work, but it also may increase soil susceptibility to dust production by mechanical disturbance. Hypothetically, as tillage implements encounter soil with a larger WMPD, much of the tillage energy will be used to breakdown the aggregates. On the other hand, if a tillage implement encounters a soil with a smaller WMPD, or a finer soil, a smaller portion of

Table 2
Point sampler test data, emissions model results and test quality ratings for Sweet Haven Dairy, Burrell, CA[a]

Sweet Haven Dairy, Burrel, CA			Soil and atmospheric conditions				Emission factor (mg m^{-2})[b]				Test ratings[c]				
Date	Operation	x loc[a] (m)	Temp (°C)	RH%	Soil Water (GWC)	WMPD (mm)	Line	Log	Block	Box	Qup A–E	Qwd >45°	Qwd SD>25°	EFU >20%	TOT
22/5/04	First disking	3	22.1	43.8	0.04		**554 (114)**	532 (114)	578 (220)	747	A	35	35	21%	C
		25	22.4	43.0	0.07		221 (31)	**248 (31)**	322 (75)	179	A	36	29	13%	B
		64	23.2	39.3	0.07		**147 (20)**	177 (23)	783 (112)	72	A	17	37	14%	B
22/5/04	Second disking (w/roller)	4	25.7	34.5	0.05		1755 (138)	**1568 (102)**	2442 (226)	2626	A	−14	12	6%	A
		22	26.0	33.7	0.04		766 (106)	**740 (72)**	798 (204)	1053	A	−15	16	10%	A
		57	26.1	32.2	0.06		**796 (54)**	916 (43)	852 (150)	707	A	−19	10	7%	A
7/6/04	Third disking (w/roller)	6	22.3	39.9	0.15		**176 (435)**	188 (464)	−225 (−693)	375	D	16	11	247%	E
		27	22.4	38.5	0.16		143 (17)	179 (25)	**156 (32)**	128	A	21	12	21%	B
		66	23.4	34.7	0.14		1564 (201)	7E + 20 (2E + 20)	**72 (13)**	13	A	31	12	18%	A
7/6/04	ST planting	5	27.6	25.1	0.09		179 (19)	166 (20)	**183 (32)**	176	C	24	13	18%	C
		34	27.9	23.6	0.06		87 (13)	**77 (14)**	86 (13)	121	A	20	12	18%	A
		77	28.2	22.0	0.09		**26 (12)**	24 (13)	20 (5)	42	A	18	17	47%	B
24/5/04	**Strip-tilling**	0	18.8	46.9	0.12		**181 (33)**	206 (39)	112 (38)	176	A	−8	13	18%	A
		16	18.9	46.1	0.09		−31 (−9)	−22 (−7)	−15 (9)	**−17**	E	−14	30	NA	F
		49	19.6	43.9	0.12		−52 (−14)	−14 (−6)	0 (83)	**−2**	D	−31	40	NA	E
24/5/04	**CT planting**	0	21.9	38.2	0.10		302 (46)	344 (50)	**319 (81)**	131	A	−10	26	26%	C
		16	22.2	36.7	0.11		15 (5)	13 (5)	10 (3)	**24**	A	37	48	NA	B
		50	22.5	35.9	0.11		0 (1)	0 (1)	0 (0)	**0**	A	48	54	NA	C
25/4/05	First disking	6	21.7	39.8	0.16	25.2	115 (20)	**134 (20)**	131 (48)	71	A	15	43	15%	B
		6	21.9	37.7	0.14	23.4	161 (31)	139 (23)	**157 (51)**	225	A	7	30	33%	C
		6	22.0	35.5	0.15	31.9	141 (25)	**143 (21)**	155 (69)	112	A	7	30	15%	B
26/4/05	Second disking (w/roller)	5	22.3	39.8	0.12	7.9	494 (52)	**535 (47)**	659 (122)	394	A	15	26	9%	B
		3	23.3	38.4	0.10	12.2	276 (28)	**293 (22)**	309 (61)	293	A	46	18	8%	B
		4	24.0	37.9	0.10	17.5	267 (32)	**298 (23)**	321 (92)	227	A	52	13	8%	B
13/5/05	Third disking (w/roller)	5	23.7	48.1	0.16	16.9	467 (39)	**443 (30)**	519 (78)	510	A	4	19	7%	A
		4	25.0	44.3	0.16	27.5	599 (49)	**563 (38)**	637 (99)	653	A	−4	20	7%	A
		4	26.1	38.3	0.15	22.4	247 (34)	**207 (28)**	240 (69)	324	A	3	26	14%	B
14/5/05	ST planting	4	24.9	38.9	0.15	18.9	296 (17)	**335 (17)**	331 (41)	238	A	7	14	5%	A
		5	27.1	33.7	0.17	22.7	164 (17)	184 (15)	**203 (38)**	154	A	26	20	19%	A
		7	29.3	28.4	0.17	16.0	290 (26)	**253 (20)**	287 (54)	361	A	16	16	8%	A

Table 2 (*continued*)

Sweet Haven Dairy, Burrel, CA			Soil and atmospheric conditions				Emission factor (mg m^{-2})[b]				Test ratings[c]				
Date	Operation	x loc[a] (m)	Temp (°C)	RH%	Soil Water (GWC)	WMPD (mm)	Line	Log	Block	Box	Qup A–E	Qwd >45°	Qwd SD>25°	EFU >20%	TOT
24/5/05	**Strip-tilling**	8	30.8	29.3	0.20	25.1	246 (35)	**217 (30)**	227 (73)	264	A	14	22	14%	A
		13	31.5	26.2	0.16	29.2	219 (12)	**202 (10)**	226 (29)	239	A	4	8	5%	A
		8	31.8	27.6	0.15	25.9	143 (14)	**122 (13)**	134 (26)	211	A	14	10	11%	A
25/5/05	**CT planting**	5	32.9	23.6	0.16	22.2	**441 (30)**	420 (27)	489 (90)	320	A	6	10	7%	A
		5	34.2	22.0	0.16	18.0	343 (26)	**329 (21)**	384 (53)	392	A	17	15	6%	A

[a] x loc is the upwind tractor distance from the vertical profiling tower at the beginning of a test period.

[b] Bold emission factors indicate those chosen based on plume profile and r^2 values. Bold operations indicate CT operations. Values in parentheses are uncertainties.

[c] Qup, upwind qualifier; Qwd >45°, wind direction qualifier; Qwd SD >25°, wind direction standard deviation qualifier; EFU >20%, relative emissions factor uncertainty = (calculated uncertainty/emission factor) × 100.

Table 3
Point sampler test data, emissions model results and test quality ratings for Barcellos Farms, Tipton, CA[a]

Barcellos Farms, Tipton, CA			Soil and atmospheric conditions				Emission factor (mg m^{-2})[b]				Test ratings[c]				
Date	Operation	x loc[a] (m)	Temp (°C)	RH%	Soil Water (GWC)	WMPD (mm)	Line	Log	Block	Box	Qup A–E	Qwd >45°	Qwd SD>25°	EFU >20%	TOT
7/5/04	First disking	1	24.4	32.0	0.06		368 (56)	**351 (52)**	381 (111)	488	A	−45	25	15%	A
		22	24.7	30.3	0.06		237 (65)	**238 (63)**	199 (64)	291	A	−24	74	26%	C
		56	25.5	30.3	0.08		**167 (21)**	208 (28)	360 (56)	74	A	14	29	12%	B
7/5/04	Second disking	9	29.3	23.8	0.05		1049 (82)	**977 (73)**	1075 (111)	1443	A	29	18	7%	A
		28	29.4	23.5	0.06		**1040 (60)**	1102 (56)	1073 (120)	904	A	22	13	6%	A
		71	29.6	22.5	0.28		631 (38)	**732 (39)**	705 (83)	502	A	14	14	5%	A
14/5/04	Listing	9	19.7	44.8	0.06		489 (33)	**411 (26)**	457 (51)	764	A	52	5	6%	B
		38	19.9	46.4	0.07		**771 (68)**	819 (70)	788 (98)	585	A	19	17	9%	A
		89	20.7	43.1	0.10		512 (25)	**663 (28)**	739 (55)	355	A	23	8	4%	A
3/6/04	Bed disking	12	29.5	27.6	0.16		49 (8)	**43 (10)**	47 (10)	75	A	−19	19	24%	B
		47	30.2	28.9	0.15		**7 (12)**	7 (13)	7 (5)	11	A	−15	19	179%	B
3/6/04	Bed mulching	12	33.6	19.3	0.12		120 (14)	128 (17)	**131 (25)**	109	A	−18	12	19%	A
		47	34.2	18.7	0.11		**47 (7)**	47 (9)	51 (7)	50	A	−29	14	15%	A
3/6/04	Ring roller	12	35.4	14.5	0.11		787 (44)	**653 (33)**	735 (58)	1169	A	−31	11	5%	A
		47	35.0	16.2	0.09		451 (29)	**479 (27)**	513 (54)	500	A	−35	15	6%	A
4/6/04	ST planting	12	22.2	41.8	0.14		**96 (14)**	103 (15)	78 (20)	87	A	43	23	14%	A
		47	23.5	36.2	0.15		NA	NA	−6 (−2)	**−4**	E	51	30	NA	G
4/6/04	Ring roller	12	25.0	34.9	0.08		247 (42)	370 (81)	**268 (84)**	296	A	28	26	31%	C
		47	25.8	34.3	0.07		125 (13)	133 (13)	**104 (29)**	87	A	16	18	28%	B
13/5/04	**CT planting**	3	18.5	47.1	0.23		−611 (−116)	−95 (−18)	**394 (90)**	136	A	−20	15	23%	B
		26	20.6	38.8	0.24		2 (6)	2 (6)	**2 (9)**	1	C	−37	39	477%	E
20/5/05	First disking	7	20.6	59.0	0.23	39.6	**66 (4)**	65 (5)	75 (8)	61	A	−4	10	6%	A
		5	21.2	56.7	0.20	32.7	**65 (6)**	63 (8)	68 (12)	49	A	20	20	10%	A
		6	21.4	54.4	0.21	31.4	20 (6)	20 (8)	**23 (3)**	11	A	10	13	13%	A
20/5/05	Second disking	4	21.8	46.4	0.20	26.8	189 (12)	**194 (11)**	203 (29)	120	A	26	11	6%	A
		5	21.7	46.5	0.19	16.7	**107 (8)**	105 (12)	87 (14)	84	A	20	10	7%	A
		3	22.0	46.2	0.18	25.1	**70 (7)**	67 (9)	74 (16)	52	A	13	11	10%	A
21/5/05	Circle harrow	5	23.0	45.7	0.16	13.3	310 (63)	303 (45)	**337 (149)**	138	A	37	16	44%	B
		6	23.6	42.4	0.19	10.3	**178 (44)**	200 (44)	122 (72)	159	A	31	45	25%	C
		6	25.5	40.2	0.19	12.8	250 (66)	244 (58)	**276 (135)**	196	A	46	43	49%	D

Table 3 (*continued*)

Barcellos Farms, Tipton, CA			Soil and atmospheric conditions				Emission factor (mg m^{-2})[b]				Test ratings[c]				
Date	Operation	x loc[a] (m)	Temp (°C)	RH%	Soil Water (GWC)	WMPD (mm)	Line	Log	Block	Box	Qup A–E	Qwd >45°	Qwd SD>25°	EFU >20%	TOT
21/5/05	Listing	6	27.8	36.9	0.19	8.6	521 (88)	498 (74)	**563 (255)**	376	A	−1	18	45%	B
		12	28.2	35.2	0.19	8.8	**418 (60)**	402 (47)	441 (154)	373	A	−35	26	14%	B
		9	27.7	37.9	0.19	12.0	**418 (51)**	381 (43)	435 (114)	382	A	−25	26	12%	B
6/6/05	Bed disking	4	20.2	39.2	0.16	37.5	199 (23)	**211 (22)**	232 (46)	195	A	9	19	10%	A
		27	20.1	41.2	0.17	43.6	94 (15)	**81 (15)**	89 (22)	126	A	2	26	18%	B
		50	20.5	37.7	0.17	50.7	29 (9)	28 (9)	**34 (9)**	18	A	−35	11	28%	B
6/6/05	Bed mulching	4	23.1	28.4	0.15	27.4	497 (55)	455 (47)	**518 (108)**	406	A	35	23	21%	B
		27	22.8	29.7	0.16	25.6	436 (40)	**410 (36)**	451 (81)	426	A	−19	21	9%	A
		50	23.2	30.5	0.14	23.4	217 (27)	**223 (27)**	250 (56)	183	A	1	24	12%	A
7/6/05	ST planting	4	24.2	24.3	0.16	5.2	961 (135)	**757 (107)**	834 (196)	1296	A	24	29	14%	B
		27	23.9	22.5	0.18	5.4	**361 (25)**	423 (26)	188 (47)	199	A	−41	15	7%	A
		50	23.9	25.5	0.19	6.6	**325 (23)**	384 (25)	340 (58)	137	A	−7	15	7%	A
7/6/05	**CT planting**	3	19.4	44.9	0.21	43.4	285 (41)	287 (36)	**319 (93)**	206	A	7	26	29%	C
		5	20.8	39.7	0.17	46.6	137 (18)	116 (14)	**130 (35)**	68	A	18	19	27%	B

[a] x loc is the upwind tractor distance from the vertical profiling tower at the beginning of a test period.

[b] Bold emission factors indicate those chosen based on plume profile and r^2 values. Bold operations indicate CT operations. Values in parentheses are uncertainties.

[c] Qup, upwind qualifier; Qwd >45°, wind direction qualifier; Qwd SD >25°, wind direction standard deviation qualifier; EFU >20%, relative emissions factor uncertainty = (calculated uncertainty/emission factor) × 100.

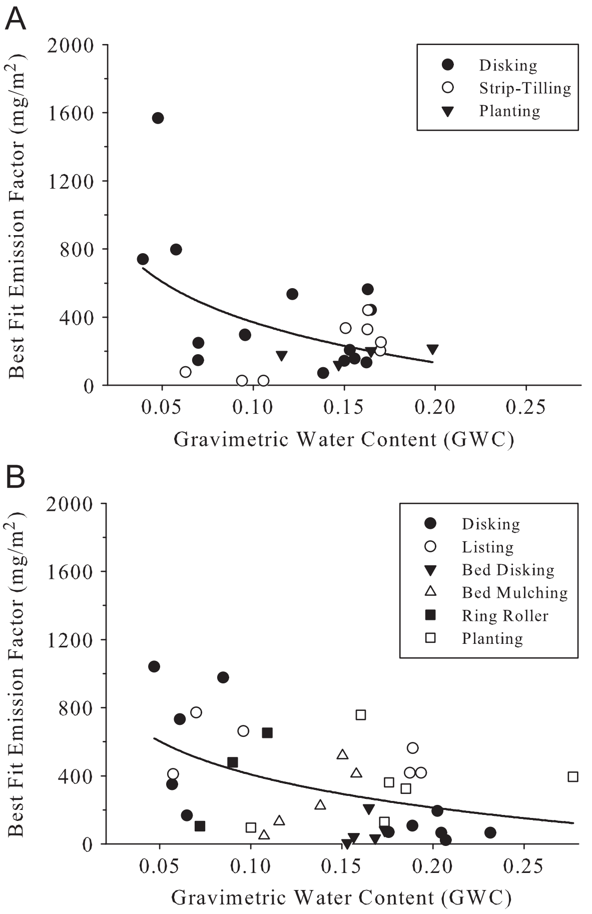

Fig. 3. Best-fit PM_{10} emission factors per operation as a function of gravimetric water content (GWC) at Sweet Haven Dairy (A) and Barcellos Farms (B). Soil surface textures at Sweet Haven Dairy and Barcellos Farms were fine sandy loam and loam, respectively. Only emission factors having a test grade of A or B were used. Equations for trendlines in graph (A) and (B) are $Y = -342\,\mathrm{Ln}(X) - 417.1$, $r^2 = 0.23$, and $Y = -280.2\,\mathrm{Ln}(X) - 237.2$, $r^2 = 0.21$, respectively.

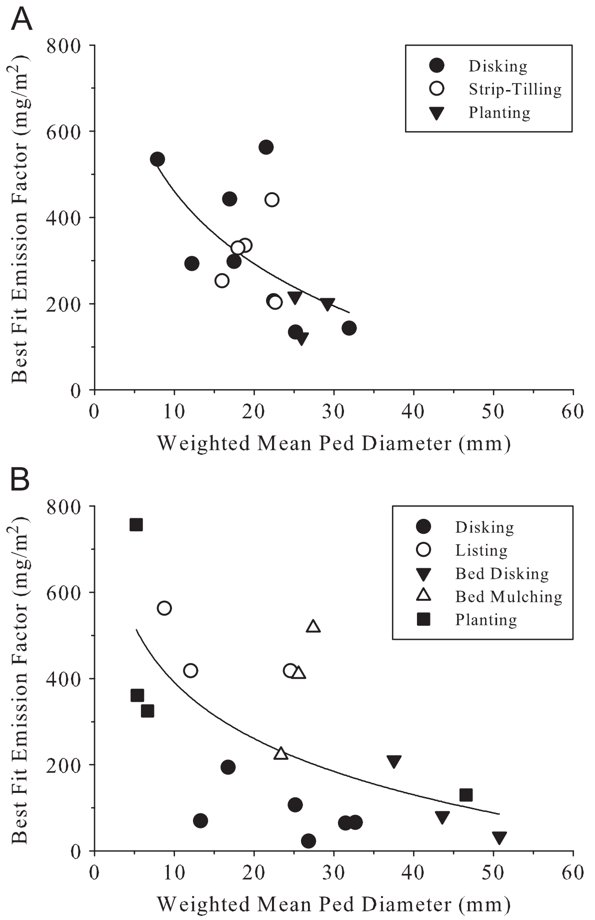

Fig. 4. Best-fit PM_{10} emission factors per operation as a function of weighted mean ped diameter (WMPD) at Sweet Haven Dairy (A) and Barcellos Farms (B). Soil surface textures at Sweet Haven Dairy and Barcellos Farms were fine sandy loam and loam, respectively. Only emission factors having a test grade of A or B were used. Equations for trendlines in graph (A) and (B) are $Y = -242.5\,\mathrm{Ln}(X) - 1019.3$, $r^2 = 0.37$, and $Y = -188.1\,\mathrm{Ln}(X) - 824.1$, $r^2 = 0.42$, respectively.

the tillage energy will be used for aggregate breakdown, and more energy may be directed towards lofting soil particles. Thus, the breakdown of the aggregates produces a larger percentage of smaller soil particles that are more likely to be suspended. Fig. 4 shows the relationship between calculated PM_{10} emission factors (only tests given an A or B grade) and WMPD at each dairy. Again, there seems to be an inverse relationship between WMPD and PM_{10} ($r^2 = 0.37$ at Sweet Haven Dairy and $r^2 = 0.42$ at Barcellos Farms). Potential interactions between GWC and WMPD, a topic we are currently researching, may account for the low r^2 values.

The importance of WMPD is accentuated when trying to: (1) determine a single emission factor for a specific operation, such as disking, which progressively pulverizes the soil with each additional pass, and (2) when determining the 'dustiest' of operations. Point one can be exemplified when comparing calculated PM_{10} emission factors for the first and second disking at Barcellos Farms in Spring 2005 (Table 3). The second disking had a higher PM_{10} emission factor ($51–123\,\mathrm{mg\,m^{-2}}$) despite little change in soil moisture (0.21–0.20). However, soil WMPD decreased from 30.3 to 18.4 mm from the first disking to the second. Point two is exemplified when comparing the PM_{10} emission factors for ST planting and bed mulching for Barcellos Farms in 2005 (Table 4). Again, without any significant changes in soil moisture (0.15–0.17), the ST planting had a higher PM_{10} emission factor than the bed mulching ($481–384\,mg\,m^{-2}$) despite the fact planting is a much less violent tillage operation than bed mulching. The difference in WMPD between these operations was 5.7 and 25.5 mm. Clearly, greater PM_{10} emissions are related to smaller WMPD for a given soil.

3.5. *Effects of atmospheric conditions on PM_{10} emission factors*

Unlike other PM studies (Holmen et al., 2001b; Clausnitzer and Singer, 2000; Kantamaneni et al., 1996), which have correlated varying atmospheric conditions (e.g., air temperature and relative humidity) with fluctuations in PM emissions, this study showed no consistent relationships between different operations. Highly variable environmental conditions for any single operation made comparisons difficult.

3.6. *Comparison to CARB emission factors*

The PM_{10} emission factors calculated in this study vary considerably from those published by CARB (Table 4) despite using very similar sampling and modeling methods. For example, the emission factor for second disking in spring 2004 at Sweet

Table 4

Averaged PM_{10} emission factors for ST and CT systems based on test grades vs. California Air Resources Board (CARB) emission factors for similar operations[a]

Season/year	Operations	Avg. EF ($mg\,m^{-2}$)	CARB EF ($mg\,m^{-2}$)	Test grades	% deviation[b]
Sweet Haven Dairy, Burrel, CA					
Spring 2004	First disking	198	135	B, B	−47
	Second disking (w/roller)	1035	135	A, A, A	−667
	Third disking (w/roller)	114	135	B, A	16
	ST planting	103	90	A, B	−14
	Strip-tilling	181	135	A	−34
	CT planting	26	90	B	71
Spring 2005	First disking	139	135	B, B	−3
	Second disking (w/roller)	375	135	B, B, B	−178
	Third disking (w/roller)	404	135	A, A, B	−199
	ST planter	263	90	A, A, A	−192
	Strip-tilling	180	135	A, A, A	−33
	CT planting	385	90	A, A	−328
Barcellos Farms, Tipton, CA					
Spring 2004	First disking	259	135	A, B	−92
	Second disking	917	135	A, A, A	−579
	Listing	615	90	B, A, A	−583
	Bed disking	25	135	B, B	81
	Bed mulching	89	135	A, A	34
	Ring roller	566	90	A, A	−529
	ST planting	96	90	A	−7
	Ring roller	104	90	B	−16
	CT planting	394	90	B	−338
Spring 2005	First disking	51	135	A, A, A	62
	Second disking	123	135	A, A, A	9
	Circle harrow	337	1403	B	76
	Listing	466	90	B, B, B	−418
	Bed disking	109	135	A, B, B	19
	Bed mulching	384	135	B, A, A	−184
	ST planting	481	90	B, A, A	−434
	CT planting	130	90	B	−44

[a] Bold operations indicate CT operations.

[b] Positive percentages indicate overestimation and negative percentages indicate underestimation of CARB's PM_{10} emission factors.

Haven Dairy was $1035\,mg\,m^{-2}$ vs. $135\,mg\,m^{-2}$ for CARB for disking. In fact, in the majority of comparisons, CARB's emission factors underestimated PM_{10} emissions measured in our study, suggesting the possibility of substantial uncertainties in CARB's data. Despite these uncertainties, the current methods used by CARB are a step in the right direction and would only benefit by incorporating the effects of varying field conditions and sequential tillage operations in PM_{10} emission estimates.

Previous to Holmen et al.'s work, PM_{10} emissions were estimated using an equation in USEPA's guidance document, AP-42, in which soil silt content, as determined by dry sieving and calculating the percent mass $<75\,\mu m$ in diameter, was the only variable (USEPA, 1995). This definition of silt is different than that used by the Natural Resources Conservation Service (NRCS) which defines silt as the weight percentage of mineral particles between 2 and $50\,\mu m$ in diameter (USDA-NRCS, 2007). Holmen et al. (2001b) concluded that the AP-42 over predicted emissions for the majority of the tests and also stressed the need for a more robust model that accounts for a number of environmental parameters.

3.7. Comparison of emission factors by operation

Based on individual emission factors calculated for each test (Tables 2 and 3), disking was frequently the dustiest operation (maximum emission: $1568\,mg\,m^{-2}$). However, because emission factors varied between multiple diskings and changes in soil conditions, the overall mean of valid tests (i.e., tests with TOT of A or B) for disking was $390\,mg\,m^{-2}$, which was about 28% less than the PM_{10} generated by listing ($541\,mg\,m^{-2}$). Compared to other operations, disking generated 44% more PM_{10} than ST corn planting ($270\,mg\,m^{-2}$), and 47% more than bed mulching (i.e., power incorporation) ($266\,mg\,m^{-2}$).

In-the-field dust measurements made directly behind tillage implements, Baker et al. (2005) found power incorporation to be the dustiest operation ($20.4\,\mu g\,L^{-1}$ for PM_4) in an ST no cover crop treatment. This PM_4 mean was 155% more than for disking ($8.0\,\mu g\,L^{-1}$ RD), 558% more than for listing ($3.1\,\mu g\,L^{-1}$) and 1100% more than for planting cotton ($1.7\,\mu g\,L^{-1}$ RD). Clausnitzer and Singer (1996) found the PM_4 mean for second and third disking ($4.94\,\mu g\,L^{-1}$) to be 52% less than for the dustiest operations, land planing ($10.29\,\mu g\,L^{-1}$) and ripping ($10.34\,\mu g\,L^{-1}$), and 384% more than for corn planting ($1.02\,\mu g\,L^{-1}$). Despite Baker et al. (2005) and Clausnitzer and Singer (1996) finding significant covariance ($p<0.0001$) between operation and PM_4 production, there seems to be no consistency in the dust potential of a particular operation or which operation will be the dustiest in a tillage sequence. This emphasizes the need to reevaluate the notion of a single emission factor for each operation and be more conscience of the field conditions at the time of an operation.

4. Conclusion

It is clear that CT can reduce PM_{10} emissions from agricultural operations. However, large variability in measured PM_{10} emissions, as a function of varied environmental conditions, sequential operations and the effects of these operations on GWC and WMPD suggest that current CARB emission factors need to be revised. In particular, the emission factors need to account for soil texture, GWC, sequential operations and WMPD. The vertical profiling method would also benefit from the use of additional profile samples to improve the 'best-fit' profiles, restricting sampling to periods of reliable, steady winds, and eliminating tests when downwind PM_{10} concentrations are close to background concentrations. Though Holmen et al. (2001b) showed no effect of downwind tractor distance from sampling tower on calculated PM_{10} emission factors, it is clear in this study that an increase in distance from tractor the sampler resulted in a decrease in PM_{10} emissions for the same operation. Thus, the assumptions of the vertical profiling method need to be reevaluated. Furthermore, since CARB emission factors were mostly lower than the emission factors measured in this study, adoption of CT and eliminations of operations should have a much larger effect than currently estimated.

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