American Industrial Hygiene Association Journal

ISSN: 0002-8894 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/aiha20

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To cite this article: Mark J. Nieuwenhuijsen & Marc B. Schenker (1998) Determinants of Personal Dust Exposure During Field Crop Operations in California Agriculture, American Industrial Hygiene Association Journal, 59:1, 9-13, DOI: 10.1080/15428119891010271

To link to this article: https://doi.org/10.1080/15428119891010271

Published online: 04 Jun 2010.

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Determinants of Personal Dust Exposure During Field Crop Operations in California Agriculture

The aim of this study was to identify determinants, if any, of personal dust exposure levels during agricultural field crop operations in California. Personal dust concentrations were measured with four-stage cascade impactors and respirable dust cyclones. Altogether, 57 cascade impactor measurements and 63 cyclone measurements were used for analyses. High personal dust concentrations were measured during most operations, in particular during ground preparation operations such as land planing and discing. For the larger dust particles, which is dust collected on all stages of the cascade impactor and dust with a 50% cutoff < 9.8 μm, the most important determinants of personal dust exposure were the presence of an enclosed cabin, relative humidity, type of operation, and tractor speed. The presence of an enclosed cabin on the tractor, higher relative humidity, and lower tractor speed were all associated with a decrease in personal dust levels. For smaller dust particles, which is dust with a 50% cutoff < 3.5–4 μm, the presence of an enclosed cabin, relative humidity, and soil temperature appear to be related to dust levels. The results of this study could be used to reduce the high levels of personal dust exposure currently experienced by those who work in field crop farming in California.

Keywords: agriculture, cabin, cascade impactor, cyclone, determinants, dust

Farming has been associated with a wide variety of hazardous exposures,[(1)] including airborne exposures, which have been associated with respiratory disease.[(2–6)] The development of respiratory disease depends on the nature, level, and particle size distribution of airborne exposures, among other issues. Several studies have reported high levels of dust exposure during field crop operations, in particular for operations such as ground preparation and harvesting.[(7–12)] Dust levels were considerably lower when an enclosed cabin was present on the tractor.[(9–12)]

In California, farm size, quantity and variety of commodities, agricultural practices, soil types, and climate are extremely diverse and substantially different from those in other parts of the United States and the rest of the world. In 1993 California's farmers sold an estimated $19.9 billion of farm products, making it the largest agricultural state in the United States based on cash receipts. That year California had some 76,000 farms, with an average size of 391 acres.[(13)] An estimated 1.5 million people were directly employed.[(14)] California agriculture produces approximately 250 different crops, and the state leads the nation in the production of over 60 crops and livestock commodities including eggs, broccoli, almonds, lemons, wine grapes, and safflower.[(13)]

Previously the authors reported on dust levels experienced by farm workers on a fruit and nut, a dairy, and a field crop farm.[(12)] This article considers the measurement data from the field crop farm. The aim was to identify determinants, if any, of personal dust exposure levels during agricultural field crop operations in California. Determinants are factors that are associated with some of the variation in exposure levels. To identify the determinants of dust

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This work was supported by the National Institute for Occupational Safety and Health, cooperative agreement U07/CCU906162-05, and the National Institute for Environmental Health Science, Center grant 1 P30 ES05707.

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exposure a technique called empirical modeling was used. For empirical modeling, information on possible determinants of the exposure are gathered during the sampling period. Associations between the measured exposure and the possible determinants are explored with regression techniques. Empirical modeling has been successfully applied in the rubber industry,[15] in animal research institutes,[16,17] in pig farms,[18] and in car component manufacturing[19] to identify determinants of exposure.

Material and Methods

As described before,[12] three experimental farms were selected around Davis, Calif. For the analyses presented in this article only measurements from the field crop farm were used. On this farm corn, tomatoes, and wheat (72 acres) were grown. Working practices and commodities were similar to those on other farms in Northern California, but the size of the farm and the plots were smaller than the average Northern California farm. The soil type was Class I agricultural soil and belonged to Yolo, Reiff, and Zamora soil series. These are soils with loam to silt loam textures, ranging to clay loams and silty clay loams. Dust concentrations were measured during all operations (Table I) in the growing season (April–November). Measurements were taken approximately 50% of the time when an operation was being performed.

TABLE I. Dust Levels (mg/m³) by Presence of Cabin

		No Cabin			Cabin		
Operation	**Particle Sizes**	**n**	**GM**	**(GSD)**	**n**	**GM**	**(GSD)**
Land planing	all stages	16	47.0	(2.0)	0		
	< 9.8 µm		2.4	(2.4)			
	< 3.5 µm		0.3	(2.6)			
	cyclone	12	0.5	(2.5)	0		
Discing	all stages	10	81.9	(2.9)	8	1.6	(1.9)[A]
	< 9.8 µm		3.3	(3.0)		0.3	(2.0)[A]
	< 3.5 µm		0.4	(3.3)		0.1	(2.0)
	cyclone	16	0.6	(3.7)	7	0.1	(2.3)[A]
Other ground preparations	all stages	6	18.1	(2.3)	4	2.2	(2.0)[A]
	< 9.8 µm		0.8	(2.8)		0.3	(3.4)
	< 3.5 µm		0.2	(2.4)		0.1	(3.2)
	cyclone	7	0.4	(1.9)	6	0.2	(1.2)
Planting	all stages	5	25.5	(1.6)	0		
	< 9.8 µm		1.9	(2.4)			
	< 3.5 µm		0.2	(2.8)			
	cyclone	6	0.2	(1.9)	0		
Harvesting	all stages	0			5	1.4	(1.9)
	< 9.8 µm					0.2	(1.8)
	< 3.5 µm					0.1	(2.1)
	cyclone	0			3	0.1	(1.2)
Fertilizing	all stages	3	10.0	(1.4)	0		
	< 9.8 µm		0.4	(2.2)			
	< 3.5 µm		0.1	(1.4)			
Mowing	cyclone	3	0.3	(1.4)	0		
Cultivating	cyclone	3	0.3	(1.4)	0		

Notes: n = number of samples; GM = geometric mean; GSD = geometric standard deviation.
[A]$p < 0.05$ for the mean exposure levels when cab is present or cab is not present

Workers on the farm were asked to wear one of two sampling devices: (1) a four-stage personal Sierra Marple 294 cascade impactor (Graseby Andersen, Smyrna, Ga.) (50% cut points at 21.3 µm, 14.8 µm, 9.8 µm, and 3.5 µm, plus one backup filter) containing Mylar™ membranes coated with a Dow Corning silicone 316 spray (Graseby Andersen) and connected to a personal sampling pump running at 2 L/min; or (2) a personal respirable dust cyclone (BGI Inc, Waltham, Mass.), containing a 37-mm diameter polyvinyl chloride filter (pore size 5 µm), connected to a small pump running at 2.2 L/min (50% cut point at 4 µm). The samplers were worn consecutively. The membranes and filters were weighed before and after sampling on a six-figure ATI Cahn C-35 microbalance (ATI Orion Cahn, Boston, Mass.). For the cascade impactor, weights were corrected for internal loss and inlet efficiency. The sampler efficiency correction factors for the stages were, from top to bottom: 0.26, 0.70, 0.82, 0.94, and 0.99.[20] Dust measured on all stages represents approximately the inhalable dust fraction, dust with a 50% cutoff < 9.8 µm of the thoracic dust fraction, and dust with a 50% cutoff < 3.5 µm of the respirable dust fraction.[12] For the cascade impactor the detection limit for each stage was 0.031 mg and 0.015 mg for the backup filter; for the cyclone the detection limit for the filters was 0.022 mg. For the cascade impactor measurements 5.3% of the first (top) stage, 14.0% of the second stage, 15.8% of the third stage, 19.3% of the fourth stage, and 35.1% of the backup stage were below the detection limit. Of the cyclone measurements, 17.5% were below the detection limit. Measurements with values below the detection limit were assigned half the value of the detection limit for statistical analyses.

For the analyses presented only operations with three measurements or more were used to obtain reasonably stable dust level estimates for the various operations (Table I). Description of the farm operations has been given elsewhere.[12] Listing, incorporating, rolling, ripping, and ploughing—operations with few measurements—were put together in a category called “other ground preparation operations.” There were enough measurements for land planing and discing to be left as separate categories. For both the cascade measurements and the cyclone measurements, one measurement was identified as an outlier during the analyses of variance process and was subsequently omitted. Cascade impactor measurements with a sampling time shorter than 20 minutes were not used for the analyses. This left 57 cascade impactor measurements and 63 cyclone measurements for analysis. The median sampling time for the cascade impactor was 55 minutes and for the cyclone 72 minutes. Both the cascade impactor and respirable cyclone measurements described log-normal distributions after splitting them up by the presence or absence of an enclosed cabin on the tractor (see Results). The possible determinants of interest were the type of operation; tractor characteristics such as presence of an enclosed cabin, tractor direction (north-south or vice versa, or east-west or vice versa) and tractor speed; and weather characteristics such as air temperature, relative humidity, rainfall, soil temperature, wind speed, and wind direction. No rainfall was observed during the measurement period, except for a few sprinkles on the last measurement day. The weather data were obtained from a weather station on the farm.

The SAS software package (SAS Institute, Cary, N.C.) was used for statistical analyses. Regression analysis and analysis of variance and covariance models were created using Proc GLM. Standard techniques such as residual plots and outlier detection were used to evaluate the models. Proc Corr was used to obtain correlation coefficients, and Proc Means and Proc Univariate to calculate mean, standard deviation, and to test for normality.

RESULTS

Dust Levels and Predictor Characteristics

High dust levels were measured for all the field crop operations, in particular during ground preparation operations such as land planing and discing (Table I). The presence of an enclosed cabin on the tractor was a strong determinant of the dust exposure levels. For example, dust exposure levels were reduced more than 50 times for dust collected on all stages of the cascade impactor during discing (Table I). Initial analyses showed that none of the other determinants, such as weather and tractor characteristics, were associated with the dust levels when an enclosed cabin was present on the tractor. The following analyses were therefore restricted to the measurements where there was no enclosed cabin on the tractor (n = 40 for the cascade impactor measurements and n = 47 for the cyclone measurements). The means and ranges for possible determinants were similar for the cascade impactor measurements and the cyclone measurements (Table II). Table III shows the correlation between various possible determinants and, as might be expected, a strong correlation was observed between relative humidity and air temperature. In general, in the morning the relative humidity was comparatively high and the air temperature comparatively low. During the day the air temperature increased and the relative humidity dropped. No explanation could be found as to why soil temperature and air temperature were correlated during the cyclone measurements and not during the cascade impactor measurements.

TABLE II. Characteristics of Various Predictor Variables

Predictor	Mean	Minimum	Maximum
Cascade impactor measurements (n = 40)			
Tractor speed (m/sec)	2.0	0.9	2.9
Air temperature (°C)	20.0	9.9	26.0
Relative humidity (%)	45.2	14.2	82.4
Soil temperature (°C)	17.0	13.8	29.9
Wind speed (m/sec)	2.7	0.4	5.3
Cyclone measurements (n = 47)			
Tractor speed (m/sec)	1.9	0.8	3.1
Air temperature (°C)	21.2	10.1	34.1
Relative humidity (%)	41.5	14.7	73.7
Soil temperature (°C)	17.5	14.0	25.8
Wind speed (m/sec)	2.8	0.8	6.1

TABLE III. Pearson Correlations Between Various Predictor Variables

	Tractor Speed	Air Temperature	Relative Humidity	Soil Temperature
Cascade impactor measurements (n = 40)				
Air temperature	−0.02			
Relative humidity	−0.23	−0.73[A]		
Soil temperature	0.08	0.08	−0.03	
Wind speed	0.35[A]	0.10	−0.26	0.07
Cyclone measurements (n = 47)				
Air temperature	−0.21			
Relative humidity	−0.15	−0.58[A]		
Soil temperature	−0.12	0.65[A]	−0.15	
Wind speed	0.26	−0.01	−0.25	0.07

[A]$p < 0.05$

Single Predictor Models with All Measurements

Table IV shows the results of various analyses of variance models with log-transformed dust exposure as dependent variable and various predictor variables (the possible determinants). Only one predictor variable was used for each model. Relative humidity was the most prominent predictor for the larger as well as the smaller dust fraction. For dust measured on all stages of the cascade impactor and for the cyclone measurements it explained 24% and 34% of the variance in exposure, respectively. Tractor speed and type of operation were also associated with the measured dust levels, although not always significantly. Soil temperature was only significantly associated with small dust particles (< 3.5 μm) measured with the cascade impactor. All single predictor models showed an increase in the residuals with an increase in the dust concentrations, suggesting that the models are not optimal and that one or more important predictor variables are missing.

Multiple Predictor Models with All Measurements

Table V shows the results of two analyses of covariance models, one with log-transformed dust measured on all cascade impactor stages (Model A) and one with log-transformed dust particles with a 50% cut point smaller than 9.8 μm (Model B) as dependent variable, respectively. In each model three predictor variables—type of operation, tractor speed, and relative humidity—were entered simultaneously. Both models were highly significant, and these three significant predictor variables together explained 73% of the variance for dust on all stages and 55% for dust particles, with a 50% cut point smaller than 9.8 μm. Both models showed

TABLE IV. Significance and Explained Variance of Analyses of Variance Models with Log-Transformed Dust Exposure as Dependent Variable and Single Predictor Variables

	Cascade Impactor Measurements						Cyclone Measurements	
	All Stages		< 9.8 μm[A]		< 3.5 μm[B]			
Predictor Variable	P	R^2	P	R^2	P	R^2	P	R^2
Operation[C]	0.0005	0.43	0.008	0.32	0.12	0.18	0.29	0.14
Tractor speed	0.02	0.14	0.16	0.05	0.07	0.08	0.08	0.07
Air temperature	0.06	0.09	0.10	0.07	0.19	0.04	0.29	0.03
Humidity	0.0015	0.24	0.008	0.17	0.008	0.26	0.0001	0.34
Tractor direction[C]	0.19	0.09	0.48	0.04	0.77	0.01	0.10	0.14
Soil temperature	0.39	0.02	0.32	0.03	0.03	0.12	0.90	0.00
Wind direction[D]	0.12	0.15	0.39	0.08	0.59	0.05	0.36	0.07
Wind speed	0.41	0.02	0.97	0.00	0.59	0.01	0.50	0.01

Notes: No enclosed cabin present on tractor. p = significance value for the F test; R^2 = explained variance.
[A]< 9.8 μm = dust particles with a 50% cut point smaller than 9.8 μm
[B]< 3.5 μm = dust particles with a 50% cut point smaller than 3.5 μm
[C]Categorical value, others are continuous value
[D]Wind direction in relation to tractor direction (e.g., same as tractor direction, from the side of the tractor)

TABLE V. Analysis of Covariance Models

Source	df	MS	F value	p	RC	STD
For dust on all stages (F = 14.5, p = 0.0001, R^2 = 0.73)						
Operation	4	3.9	12.5	0.0001		
Tractor speed	1	5.7	18.3	0.0002	1.14/(m/sec)	0.27
Relative humidity	1	5.0	16.0	0.0003	–0.024/%	0.006
Error	33	0.3				
For dust particles < 9.8 μm (F = 6.6, p = 0.0001, R^2 = 0.55)						
Operation	4	4.2	6.5	0.0005		
Tractor speed	1	4.4	6.9	0.01	1.00/(m/sec)	0.38
Relative humidity	1	5.8	9.0	0.005	–0.025/%	0.008
Error	33	0.6				

Notes: Log-transformed dust concentrations (measured with the cascade impactor) as dependent variable and type of operation, tractor speed, and relative humidity as multiple predictor variables (no enclosed cabin present on tractor). df = degrees of freedom; MS = mean squares; F value = F test; p = significance value for F test; RC = regression coefficient; STD = standard error of the regression coefficient.

an acceptable distribution of the residuals. For dust particles < 3.5 μm measured with the cascade impactor, a model with two significant predictor variables—soil temperature and humidity—explained 36% of the variance. However, the residuals increased with an increase in the dust concentration, suggesting that this is not an optimal model and that one or more important predictors are missing.

Discussion

This article shows that farm workers are exposed to very high dust levels during field crop operations in California, in particular for larger dust particles, which is dust collected on all stages of the cascade impactor and dust with a 50% cutoff < 9.8 μm. The highest dust levels were measured during land planing and discing. Important determinants of these dust exposure levels, in particular for larger dust particles, were the presence of an enclosed cabin, relative humidity, type of operation, and tractor speed. Personal dust levels were considerably reduced when an enclosed cabin was present on the tractor, for example, more than fiftyfold for all dust particles during discing. An increase in the relative humidity was associated with a decrease in the measured dust levels, and an increase in the tractor speed was associated with an increase in the measured dust levels.

These results confirm earlier reports that high dust exposure levels occur during field crop operations and that cabins can significantly reduce the dust exposure experienced by farmers and farm workers.[7–11] Previously[14] in a questionnaire survey, the authors identified tractor driving as an important determinant of dust exposure among 2000 California farm operators. The results of the current study confirm this finding. Only approximately 20% of the farm operators reported having an enclosed cabin on their primary tractor. An enclosed cabin is generally not a necessity in California agriculture because of the dry and warm weather during the growing season. These weather conditions also help cause the high dust levels experienced by farmers and farm workers. An enclosed cabin would be good protection against dust and would also protect against extreme heat, provided it contains a good air conditioning unit. No relationship was found between dust and the various determinants when there was an enclosed cabin on the tractor. This is probably because an enclosed cabin creates its own microenvironment with its own determinants, which were not recorded. It could also be the result of the small number of samples.

Various researchers have used empirical modeling to identify determinants of exposure; Kromhout et al.[15] identified tasks in the rubber industry that were associated with high exposures; Nieuwenhuijsen et al.[16,17] identified tasks associated with high exposure, stock density, and ventilation rate as determinants of exposure in animal research institutes; Preller et al.[18] identified tasks with high exposure and air temperature as determinants of exposure in pig farming; and Woskie et al.[19] identified, among others, indoor humidity, machine type, and metalworking fluid type as important determinants of exposure in the car component manufacturing industry. Empirical modeling has some limitations, however. It can be used only for events that occur during the sampling period and are recorded, and it requires sufficient variation in the event. In addition, reliable estimates for the determinants are difficult to obtain when the event occurs infrequently during the sampling period. For example, during this sampling period it did not rain, except for some sprinkles during the last measurement day. Therefore, we could not assess the influence of rainfall on the dust exposure level, which is undoubtedly a strong determinant. However, it must be noted that it rarely rains during the growing season in California. Also, soil moisture was not recorded, which is probably a strong determinant of dust exposure. It is important to remember that the results might be different if the study had been carried out in other regions of the United States, because the conditions may have been completely different. The data sets were fairly small, and this could well influence some of the results; more significant associations between exposure and determinants might be observed if the number of measurements was increased, for example, for tractor direction in relation to wind direction.

This study identified some clear determinants of dust exposure such as the presence of an enclosed cabin, relative humidity, type of operation, and tractor speed. This information could be used when carrying out an epidemiological study investigating the relationship between dust exposure and respiratory disease and to develop a control strategy to reduce personal dust exposure of farmers and farm workers. The study results could also be used to generate hypotheses for additional, more detailed studies aimed at controlling exposure, for example, an in-depth study of the relationship between relative humidity and dust exposure levels. The presence of an enclosed cabin appears to be the most effective way to reduce the personal dust exposure, but it is also fairly costly. It reduces the personal dust levels up to fiftyfold (in the case of discing) and brings them well below the American Conference of Governmental Industrial Hygienists' threshold limit values for inhalable (10 mg/m^3) and respirable (3 mg/m^3) particulates not otherwise classified.[21]

Comparing the highest measured relative humidity with the lowest, relatively humidity could reduce personal dust levels for dust collected on all stages of the cascade impactor up to fivefold (using the regression coefficients from the regression models: $e^{-0.024*14.2}/e^{-0.024*82.4}$ [see also Appendix I]). Relative humidity is generally high in the morning and decreases when the temperature increases. One way to avoid high personal dust levels would be to carry out operations in the early morning, although this would limit the time one could work on the field during a single day. The type of operation was a strong determinant, but changing operations is difficult; for example, ground preparation operations need to be carried out.

There was an eightfold difference in dust levels between the lowest and highest exposed operations, fertilizing and discing, for dust measured on all stages of the cascade impactor. Comparing the highest and lowest measured tractor speeds, a reduction in tractor speed could lead to a tenfold reduction in dust levels measured on all stages of the cascade impactor, even though the variation in tractor speed is small (using the regression coefficients from the regression models: $e^{1.14*2.9}/e^{1.14*0.9}$). The log-transformed regression model is a multiplicative model and the predictors are multipliers.[19] As can be seen, there are several ways to reduce the personal dust exposure, but whether they will be used or not will depend on the attitudes of the farmers and farm workers toward dust exposure and on legislation, among other things. Farmers and farm workers often do not regard dust exposure as hazardous, even though it is well recognized as such in the literature.[1–6] In a previous study it was found that the use of protective equipment increased with an increase in exposure to noise and pesticides but not with an increase in dust exposure.[15] In another study, two-thirds of California farm operators perceived farming to be less hazardous than other occupations, and respiratory problems were their third health concern after injuries/accidents and exposure to pesticides/farm chemicals.[22] More information on health and safety needs to be provided to the 1.5 million people who work on farms in California.

In this study dust exposure was measured; but dust has many possible constituents, such as silica and silicates, endotoxins, pesticides, and allergens. More work is needed to study these constituents in dust and their health effects in California agriculture and agriculture elsewhere.

Acknowledgments

The authors would like to thank Ms. Hanneke Kruize for helping set up the study and collecting data, Dr. Steve Samuels and Dr. Noah Seixas for their advice, the management for their cooperation, and all the farm workers for their participation.

Appendix I

Regression Model and Calculation of Effects

Ln (dust concentration) = $C + \beta_1X_1 + \beta_2X_2 + ...\beta_nX_n$

β = regression coefficients

X = the independent variables, for example, relative humidity

C = intercept

exp (Ln dust concentration) = $\exp(C + \beta_1X_1 + \beta_2X_2 + ...\beta_nX_n)$

dust concentration = $\exp(C) * \exp(\beta_1X_1) * \exp(\beta_2X_2) * ...... \exp(\beta_nX_n)$

Using –0.024 (regression coefficient) from Table V and using lowest (14.2) and highest (82.4) measured relative humidity data from Table II:

$e^{-0.024*14.2}/e^{-0.024*82.4} = 0.71/0.14$ = fivefold difference

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