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A Task-based Analysis of Black Carbon Exposure in Iowa Farmers During Harvest

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Abstract

Diesel exhaust has been associated with adverse human health effects. Farmers are often exposed to diesel exhaust; however, their diesel exposure has not been well characterized. In this descriptive study, we measured black carbon concentrations as a proxy for diesel exhaust exposure in 16 farmers over 20 sampling days during harvest in southeast Iowa. Farmers wore a personal aethalometer which measured real-time black carbon levels throughout the working day, and their activities were recorded by a field researcher. Black carbon concentrations were characterized for each farmer, and by activity, vehicle fuel type, and microenvironment. Overall, 574 discrete tasks were monitored with a median task duration of 5.5 minutes. Of these tasks, 39% involved the presence of a diesel vehicle. Farmers' daily black carbon geometric mean exposures ranged from 0.1 to 2.3 $\mu\text{g}/\text{m}^3$, with a median daily geometric mean of 0.3 $\mu\text{g}/\text{m}^3$. The highest black carbon concentrations were measured on farmers who used or worked near diesel vehicles (geometric mean ranged from 0.5 $\mu\text{g}/\text{m}^3$ while harvesting to 4.9 $\mu\text{g}/\text{m}^3$ during animal work). Higher geometric means were found for near vs. far proximity to diesel-fueled vehicles and equipment (2.9 vs. 0.3 $\mu\text{g}/\text{m}^3$). Indoor, bystander proximity to diesel-operated vehicles resulted in the highest geometric mean black carbon concentrations (18 $\mu\text{g}/\text{m}^3$). Use of vehicles with open cabs had higher mean black carbon concentrations than closed cabs (2.1–3.2 vs. 0.4–0.9 $\mu\text{g}/\text{m}^3$). In summary, our study provided evidence that farmers were frequently exposed to black carbon associated with diesel-related activities at levels above urban ambient concentrations in their daily work during harvest.

Keywords

Black Carbon; Exposure; Aethalometer; Farmers; Harvest; Diesel Exhaust

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INTRODUCTION

Emissions from diesel engines are highly prevalent anthropogenic pollutants. Both short-term and chronic exposures to diesel particulate matter (DPM) from the use of diesel-fueled engines have been associated with numerous non-cancer health effects, including chiefly respiratory, cardiovascular, and neurological outcomes.^(1–3) In 2012, diesel engine exhaust was also classified as a Group 1 human carcinogen by the International Agency for Research on Cancer.⁽⁴⁾ Because of the wide-ranging health effects of DPM, DPM concentrations have been studied under a variety of environmental (i.e. in-vehicle during commuting⁽⁵⁾) and occupational exposure settings (i.e. mining,^(6, 7) railroad work,⁽⁸⁾ trucking^(9–11)).

The farming industry has been relatively overlooked in diesel exhaust exposure assessments thus far.⁽¹²⁾ However, modern farms are increasingly large scale and use heavy machinery that primarily relies on diesel engines. For example, in a subset of the large, prospective Agricultural Health Study (AHS) cohort, 97% of 14,801 Iowa farmers who completed the enrollment take-home questionnaire self-reported driving diesel tractors at least once per month.⁽¹³⁾ Nearly half (42%) of these farmers additionally reported driving diesel tractors weekly in the winter. The average number of days per growing season were 28 days for tilling soil, 24 days for driving combines, 17 days for planting crops, 28 days applying natural fertilizer and 10 days applying chemical fertilizer. These data suggest frequent DPM exposure opportunities among farmers across a variety of tasks. Moreover, driving diesel tractors has been shown to increase the odds of wheezing in farmers (OR = 1.31; 95% confidence interval = 1.13, 1.52),⁽¹⁴⁾ and driving diesel tractors on a daily basis has been shown to increase the risk of developing adenocarcinoma of the lung (RR = 3.39; 95% confidence interval: 1.23, 9.33).⁽¹⁵⁾

Diesel engine exhaust consists of a complex mixture of gases and particulates and contains 33–90% elemental carbon (EC) by mass.⁽¹⁶⁾ As a result, EC has historically been used as a surrogate measure of diesel exhaust exposure.^(9, 17) Airborne particulates are typically collected as an integrated sample on a quartz fiber filter and then analyzed for EC, organic carbon, and total carbon using the standard reference method for DPM (NIOSH method 5040, hereafter *NMAM 5040*).⁽¹⁸⁾ This approach provides a time-weighted average concentration over the sampling period, with long sampling durations needed where EC concentrations are low.⁽¹⁹⁾

To provide a more detailed characterization of DPM exposure, researchers have used direct-reading instruments that measure black carbon (BC) concentrations, which are highly correlated with EC.^(5, 20–24) BC is produced during incomplete combustion.⁽²⁵⁾ In the US, BC emissions come predominantly (52%) from the transport sector, lending support for its use as a surrogate for diesel engine exhaust.^(26, 27) Two BC real-time monitors have been used in a variety of settings.^(5, 28, 29) The Aethalometer® (Magee Scientific, Berkeley, CA) is an instrument that samples particles from an air stream onto a quartz-fiber filter where they are optically analyzed to obtain a BC mass concentration, and is typically used as an area sampler. The microAeth® (Aethlabs, San Francisco, CA) is based on the same technology and is highly sensitive, lightweight, and capable of use as a personal exposure monitoring device.⁽³⁰⁾ The microAeth® (MA) is increasingly used in personal, vehicular,

and occupational studies.^(5, 28, 31, 32) However, chamber experiments that compare the MA to a standard reference method for EC at realistic field concentrations ($25 \mu\text{g}/\text{m}^3$) are necessary to compare diesel exposure levels between studies using the two diesel exposure metrics. Obtaining an MA correction factor compared to an EC standard reference method is an important step in quantifying both occupational and general population exposures.

Given the adverse health effects of DPM, the prevalence of diesel-fueled sources on farms, and the limited DPM exposure characterization for this occupation thus far, a study evaluating farmer's DPM exposure was needed. The present descriptive study sought to characterize DPM exposure levels during farming tasks undertaken by farmers in Iowa during the fall harvest season using BC concentrations measured with the MA as a surrogate for DPM exposure. To facilitate comparisons across studies in the extant literature, a small-scale calibration study comparing the MA to the *NMAM*5040 method was also conducted to obtain a calibration factor to convert BC concentrations into an estimated EC concentration.

METHODS

Study Population

BC exposure monitoring was conducted on a subset of farmers recruited in the Biomarkers of Exposure and Effect in Agriculture (BEEA) Study. BEEA recruitment began in June 2010 and is ongoing, as previously described.⁽³³⁾ BEEA participants were recruited from the Agricultural Health Study (AHS) cohort and were eligible to participate if they were male, over 50 years of age, and had never been diagnosed with cancer (other than non-melanoma skin cancer), among other requirements. Recruitment for the exposure monitoring study began in August 2015. Eligible participants met the BEEA eligibility criteria (but were not previously enrolled in BEEA), lived in Iowa, and responded 'yes' to the question 'are you currently actively farming or participating in any farming activities in the next three months?'. Recruitment and study protocols were approved by the Institutional Review Boards of the National Cancer Institute, the University of Iowa, and Westat (Rockville, MD).

Sixteen farmers participated in BC exposure monitoring from September-November 2015 (fall harvest), with four farmers measured on two occasions, for a total of 20 monitoring days. The farmers lived in Southeast Iowa counties, and their level of involvement in farming activities ranged from very active to semi-retired. Farm operations included both row-crops (soy and corn) and animal production (beef cattle and hog). During the study period, farmers carried out various tasks related to harvest and were often operating vehicles during harvest or while transporting goods.

Exposure monitoring

Exposure monitoring was typically conducted over 7 daytime hours, prioritizing the busiest farming hours based on the farmers' expected activities obtained during a pre-visit confirmatory phone call. A field researcher (E.M.S.) observed and recorded the farmer's activities throughout the monitoring period in an activity log. The farmer was asked about any farming tasks conducted before the field researcher's arrival and about any intended

farming tasks that would occur after her departure; these later activities were noted but not measured. Farmers wore a small backpack containing an MA (microAeth® model AE51 single-wavelength, personal exposure monitor for black carbon) for the entire sampling day. The MA's built-in pump pulled air over a Teflon coated glass fiber filter, while a light beam passed over the filter and quantified the change in light attenuation due to BC. The MA has a measurement range of 0 – 1000 µg BC/m³ with a resolution of 0.001 µg BC/m³ and precision of ± 0.1 µg BC/m³.⁽³⁰⁾ A micro-cyclone (AethLabs, San Francisco, CA) was affixed to the MA inlet tubing to reduce road-dust interference from larger PM (>2.5 µm). The MA's flow-rate was set to 50 ml/min to maintain a particle cut-size of 2.5 µm. The MA was set to sample every 30 seconds over the entire sampling episode - 30-second averaged samples at a flow rate of 50 ml/min are recommended for personal exposure monitoring in high BC concentrations for occupational exposures.⁽³⁰⁾ The micro-cyclone and tubing were cleaned and the MA filter was replaced daily. The MA was calibrated using the AE51 FlowCal software (Aethlabs) and a Sensidyne Gilibrator-2 (St. Petersburg, FL, USA). On two occasions, the flow rate reported in the MA output was inadequate because of inadvertent constriction of air tubing. BC concentrations measured after the reduction in flow rate were discarded (after 1 hour of sampling on one day and after 3 hours of sampling on a second day) but were retained prior to the instrument failure.

Data Treatment and Analysis

The field researcher's observation logs were used to annotate each 30-second interval in the BC exposure files with the following eight characteristics: work task, operating vehicles/equipment class (e.g., heavy duty farm, light duty road, mixed), vehicle/equipment type (e.g., tractor, combine), fuel type (e.g., diesel, gasoline, natural gas, other combustion sources – such as biomass burning or welding fumes, electric, multiple types), vehicle details (year, make, model), farmer location (e.g., in vehicle, outdoors near/far from vehicle, indoors, indoors bystander to vehicle, micro-environment (e.g., cab open/enclosed, building open—door or windows open/closed), and non-vehicular BC sources (e.g., combustion sources, such as welding). Cigarette smoking as a potential BC source was noted during the rare cases when it was observed. A farmer location of “in vehicle” included both cab types, open or enclosed. Furthermore, we defined the “open cab” micro-environment to include any condition in which outside air easily infiltrated the cab (e.g. window or door open, or no cab present).

The following 11 activity categories were identified as commonly performed by farmers over the sampling period:

- A. *Transport Load.* Farmers transported empty or full vehicles (e.g. semi-truck, grain truck, tractor with wagon) associated with hauling loads such as grain, soy beans, or animals.
- B. *Animal Work.* Farmers carried out work related to animals (indoor or outdoor), such as checking hog buildings.
- C. *Drive.* Farmers drove vehicles that were not used for hauling; typically pickup trucks.

- D.** *Grain Bin.* Farmers worked on, in, or around grain bins, doing a variety of grain bin-related tasks.
- E.** *Harvest.* Farmers harvested crops in the field (typically with an enclosed-cab combine).
- F.** *Light Miscellaneous Farm Work.* Farmers carried out miscellaneous tasks on the farm, such as mowing the lawn.
- G.** *Load.* Farmers loaded or unloaded harvested crops to and from vehicles in a variety of settings.
- H.** *Other: Indoor.* Farmers spent time indoors, e.g. eating, socializing, completing paperwork.
- I.** *Other: Cutting Concrete.* Farmer cut concrete with a power-saw.
- J.** *Transition.* Any transitional period of time between tasks; typically 1–5 minute periods.
- K.** *Vehicle Maintenance.* Farmers performed vehicle repairs including cleaning, re-fueling, and welding/mechanical work.

The 30-second BC exposure concentrations were used to calculate the arithmetic (AM), geometric (GM) means, geometric standard deviations (GSDs), and minimum and maximum BC concentrations for each monitoring day. Data were post-processed using the manufacturer's software for consistency with other research efforts.^(25, 30) Total sample duration and duration of time spent while experiencing BC levels 10, 20, and 50 $\mu\text{g}/\text{m}^3$ were calculated and used to obtain the proportion of time in the monitoring period above each BC threshold. We identified each change in the farmer's task, where a task represented a unique combination of activity and vehicle fuel type. Recurrences of the same task were counted as a new task. The 30-second BC concentrations were also used to calculate the average task-specific BC exposure concentration and task duration. These task-specific concentrations were used to calculate the median task duration, the median proportion of time the task BC concentration exceeded various BC thresholds (10, 20, and 50 $\mu\text{g}/\text{m}^3$), and the AM, GM, GSD, and maximum BC concentration for each activity/fuel source combination. For the activity categories 'light miscellaneous farm work', 'load', and 'drive', farmer location- and microenvironment-specific BC concentrations were also calculated for tasks that included exposure to diesel exhaust. We focused primarily on the GM because the data were highly skewed to the right, but AMs were included for comparability to other publications. Total, between-farmer, between-day, between-activity and within-activity variance in BC concentrations were obtained from a mixed-effects linear regression model with log-transformed BC concentration as the dependent variable and farmer, monitoring day, and activity as random effect terms. All analyses were conducted using Stata v. 14.2 (StataCorp, College Station, Texas) with statistical significance accepted at an $\alpha = 0.05$ level.

Calibration to elemental carbon concentrations

MA BC measurements were calibrated relative to EC measurements obtained using a standard method (*NMAM 5040*).⁽¹⁸⁾ Fresh DPM was produced using a diesel generator (Red Hawk Equipment Model DG6LE, Eastern Tools and Equipment, Inc. 600 Industrial Parkway, Norwalk, OH 44857) operating at 3600 rpm under no load and dispersed into an enclosed 0.5 m³ chamber. The diesel engine exhaust was delivered to the chamber thru a 1" ID galvanized pipe, approximately 20' long. HEPA-filtered air entered the chamber and mixed with the DPM, enhanced with the use of a small fan. The MA inlet was equipped with a sharp cut micro-cyclone and operated at a flow rate of 50 ml/min for a particle cut-size of 2.5 µm. BC measurement intervals were set to 30 seconds. A co-located PM_{2.5} dust sample was collected using a 25 mm respirable dust aluminum cyclone (SKC Inc., Eighty Four, PA, USA) and a Tissuquartz™ filter (Pall Life Sciences, Ann Arbor, MI, USA) in a 3-piece, 25 mm cassette, and a sampling pump (Model 224-PCXR4, SKC Inc., Eighty Four, Pa., USA) operating at a flow rate of 3.8 l/min to obtain a cyclone cut-size of 2.5 µm (per manufacturer recommendations). All instruments were calibrated before and after each chamber trial, after which pre-and post-calibration flow rates were averaged. MA filter strips were replaced and cyclones were cleaned between chamber experiments.

In total, four chamber experiments were conducted at "low, medium, and high" BC concentrations of approximately 5, 10 and 20 µg/m³. Trial durations were varied (196, 91, and 46 minutes) to ensure a detectable amount of DPM on the filter samples. One blank was included, during which the cassette was opened inside the chamber with no airflow passing over the filter. *NMAM 5040* filter samples were analyzed by ALS Global (Salt Lake City, UT), an accredited lab for this method, and blank corrected.

RESULTS

A typical daily task sequence can be seen in Figure 1. Daily BC concentrations and sample duration of exposures over 10, 20 and 50 µg/m³ are described in Supplemental Table 1. Overall, across the 20 sampling days, the median daily GM for BC was 0.33 µg/m³ (range: 0.1–2.3 µg/m³), and the GSD was 4.5 (range: 3.1–9.3). Excluding the two shortened sample days did not meaningfully change these values. Figure 2 shows the distribution of daily AMs and GMs. All daily GMs were <1 µg/m³; with two exceptions (1.1 and 2.3 µg/m³). Daily peak BC exposures were 20 µg/m³ in 85% of the visits, and 100 µg/m³ in 40% of visits. The log-transformed BC concentrations had a between-farmer variance of 0.67 (SE = 0.13; 28% of total variance) and a within-farmer variance of 1.7 (SE = 0.10, 72% of total variance).

In total, farmers performed 574 discrete tasks, 39% of which had the presence of a diesel vehicle. The median task duration was 5.5 minutes. Activity/fuel type results are shown in Table I. Task-specific median durations ranged from 3 to 49 minutes. The longest duration tasks were the activities 'transport load' (median = 18 min.), 'other: indoor' (median = 26 min.), and 'harvest' (median = 23 min.). Average BC concentrations for tasks varied by fuel type for most activities. Higher BC GMs were observed when diesel engines were present, compared to other, or to no fuel source, for the activities 'transport load', 'animal work', 'drive', 'load', and 'vehicle maintenance', with GMs in the presence of diesel exhaust

ranging from 0.9 to 4.9 $\mu\text{g}/\text{m}^3$. Higher BC GMs were observed for other fuel types, compared to diesel fuel, for the activities 'grain bin', 'light misc. farm', and 'other', which are likely attributable to non-diesel BC sources. Of the total variance for all tasks based on log-transformed BC, 15% was between-farmer, 13% was between-day, 32% was between-activity, and 39% was within-activity variance. Incorporating activity and fuel type in the model as fixed effects had negligible change on the between-farmer and between-day variance components, but reduced the between- and within-activity variances by 27% and 2%, respectively.

Figure 3 demonstrates the variation in task-specific BC concentrations by activity category and fuel type. As shown, farmers using or in proximity to diesel fueled-vehicles had higher BC concentrations than those in proximity to other fuel types (i.e., gasoline, electric, natural gas, other).

Table II explores the effect of farmer location and microenvironment on exposure to BC during specific tasks involving diesel vehicles. For the activities 'light miscellaneous farm work', 'load', and 'drive' that occurred in the presence of diesel-fueled vehicles and equipment when the equipment was running, we further stratified the results by farmer location and microenvironment (Table II). The highest GM BC concentrations were observed while farmers were bystanders in indoor locations while vehicles were running (e.g., in a garage), while farmers were located in their vehicle, with higher exposures in open cabs than in enclosed cabs, and while they were outdoors, but near a running diesel vehicle. The lowest BC concentrations occurred when farmers were outside of their vehicle and far from operating diesel vehicles, and while they were operating a vehicle with an enclosed cab.

Calibration

Comparisons of the average BC concentration measured with the microAeth[®] to the measured concentration per *NMAM5040* as EC in the same time period for the four trials in the calibration chamber studies are shown in Figure 4. The intercept was not significantly different than 0, therefore the calibration equation was forced through 0 to provide a direct conversion factor (Equation 1).

$$EC \text{ Conc.} = BC_{MA} \text{ Avg Conc.}_T \times 1.17 - 1$$

Applying this equation to the mean daily GM BC concentrations (Supplemental Table 1) results in a mean daily GM EC concentration of 0.6 $\mu\text{g}/\text{m}^3$ (range 0.1–2.7 $\mu\text{g}/\text{m}^3$).

DISCUSSION

To our knowledge, this is the first study to characterize real-time BC concentrations of farmers exposed to diesel-fueled vehicles and equipment during harvest. Overall, we found that farmers in our study were exposed to diesel exhaust during nearly 40% of observed farming tasks, with daily AM BC concentrations ranging from 0.2 to 11.3 $\mu\text{g}/\text{m}^3$ and daily

GM BC concentrations ranging from 0.1 to 2.3 $\mu\text{g}/\text{m}^3$ (Supplemental Table 1; Figure 2). After applying the BC to EC calibration multiplier of 1.17, the corresponding daily GM EC concentrations ranged from 0.1–2.7 $\mu\text{g}/\text{m}^3$. These findings are comparable to reported GM EC concentrations of 4 $\mu\text{g}/\text{m}^3$ for the trucking industry,^(34, 35) and respirable GM EC concentrations of 1.4 $\mu\text{g}/\text{m}^3$ for bus drivers and parking attendants (booth).^(12, 36) Studies of workers in other industries with long-term diesel exhaust exposure have reported increased risks of neurological, cardiovascular and respiratory outcomes,^(1–3) as well as lung cancer.⁽³⁵⁾ In contrast, farmers have been reported to have a decreased risk of lung cancer compared to the general population,^(37–39) and few studies have investigated risk of lung cancer and diesel exhaust exposures specifically within farming populations.⁽⁴⁰⁾

Our findings suggest that farmers' exposure to diesel exhaust is similar in magnitude to vehicular-based occupations and higher than in ambient urban environments. Individual activities carried out in the presence of diesel-fueled vehicles and equipment in our study had the following average concentrations (AMs): 1.3, 1.4, 5.7, 6.2, 7.0, 7.8, 9.1, 12.3, which were similar to or higher than those observed for the task "in transport" (6.4 $\mu\text{g}/\text{m}^3$) in a study conducted in Belgium by Dons et al.⁽²⁸⁾ The seven remaining activities in the Dons et al. study had average BC exposures <3 $\mu\text{g}/\text{m}^3$, concentrations similar to those observed in this study when no diesel-fueled vehicles or equipment were nearby. In the non-occupational environment, mean annual ambient BC concentrations are often lower than these occupational levels, even in metropolitan areas. In the New York City community Air Survey, BC concentrations at 138 street-side sites averaged 1.3 $\mu\text{g}/\text{m}^3$.⁽⁴¹⁾ At a site in Rochester, New York BC concentrations averaged 0.6 $\mu\text{g}/\text{m}^3$.⁽⁴²⁾ In Southern California (2012–2013), BC concentrations at ten monitoring sites averaged 1.3 $\mu\text{g}/\text{m}^3$, with some spatial and temporal variability (winter concentrations exceeded those in warmer months).⁽⁴³⁾ EC levels in the Midwest (St. Louis area) estimated using two modeling approaches were approximately 0.8 $\mu\text{g}/\text{m}^3$.⁽⁴⁴⁾ Few data on rural BC concentrations are available, but EC measured at a rural site in Illinois (Bondville) from 2002–2005 (0.4 $\mu\text{g}/\text{m}^3$) was about half the concentration in the St. Louis study.⁽⁴⁵⁾ Similarly, two rural Swiss sites had summertime BC concentrations of 0.4, and 0.8 $\mu\text{g}/\text{m}^3$.⁽⁴⁶⁾ Higher winter concentrations of 0.8 and 2.3 $\mu\text{g}/\text{m}^3$ in that study were attributed to thermal inversions and wood-burning.

When examining the effect of microenvironment within specific farming tasks, BC concentrations were higher when the vehicle was open-cabbed versus enclosed. The within-vehicle microenvironment has been previously studied for BC exposures.^(5, 47) In-vehicle versus outdoor BC ratios can vary dramatically depending on a multitude of factors (i.e. season, road type, vehicle-type present); however, lower in-vehicle BC concentrations compared to outdoor concentrations were seen in a multi-city commuting study in Canada, where median in-vehicle BC concentrations were lower than outdoors, except during wintertime.⁽⁴⁸⁾ In-vehicle BC concentrations in a car with closed windows in Los Angeles and Sacramento, California ranged from 4.7 to 19 $\mu\text{g}/\text{m}^3$ (AMs), while driving behind 3-axle diesel vehicles and diesel passenger cars. Additionally, BC concentrations inside cars following diesel transit buses with ground-level exhaust pipes were six times higher than when following buses with high-exhaust pipes, suggesting the importance of emission source location in BC exposure.⁽⁵⁾ Lastly, the use of closed cabs on combines has been shown to provide a protection factor of 11.7 for total dust exposure,⁽⁴⁹⁾ although the

relevance to BC, which is comprised of smaller particles than total dust, is not clear. Insights to the potential effect cabs have on BC exposures may be evident from in-cabin ultrafine particle exposures, which have been studied.⁽⁵⁰⁾ Hudda et al. (2012) found in-cabin air exchange rates (AERs) to be the most significant determinant of indoor/outdoor ultrafine particle ratios.⁽⁵⁰⁾ While we did not measure in-cabin AERs in vehicle cabs in this study, farm equipment is typically operated at a slow velocity, likely resulting in low AERs, thereby reducing their potential impact on BC exposures. Previous research has not examined the role of bystander BC exposure from near-vehicle micro-environments; however, the importance of near-vehicle BC exposures has been suggested from environmental monitoring studies that found that near-highway BC concentrations decreased rapidly 17 to 150 m downwind of freeways.^(51–53) Supporting these findings, we found that BC concentrations were much higher when the farmer was in near vs. far proximity to diesel-fueled vehicles, with the highest BC concentrations observed in near proximity to diesel vehicular exhaust in an indoor environment (garage).

BC concentrations exceeding $10 \mu\text{g}/\text{m}^3$ were infrequent, ranging from 0 to 30% of a sampling day (median 3%). However, we observed two daily peak BC concentrations that exceeded $300 \mu\text{g}/\text{m}^3$. One concentration ($379 \mu\text{g}/\text{m}^3$) occurred when the farmer was standing in close proximity to two large diesel engine vehicles (combine and tractor) that were each >35 years old. EC concentrations in truck cabs can be significantly affected by vehicle age.^(10, 11) Old tractors were frequently used by the farmers in this study to power augers to transport grain from grain truck/wagon to and from bins. However, characterizing these exposures is difficult, given dynamic factors such as wind-speed, wind direction, and the presence of multiple vehicles. The second daily peak exposure of $395 \mu\text{g}/\text{m}^3$ occurred while the farmer stood very close during the ignition of an engine used to power-wash a hog confinement building.

Taken together, our data show that farming tasks involving the use of diesel fuel usually led to the highest BC concentrations, consistent with previous research demonstrating that BC could be used as a proxy for diesel exhaust exposure.⁽⁵⁴⁾ However, non-diesel BC sources were present in our study and likely influenced the measured BC concentration in some situations. For example, the task of cutting concrete had the highest BC concentrations but did not involve diesel-fueled vehicles or equipment. In this case, the high concrete dust concentrations likely interfered with light absorption. BC emissions are also associated with other farming tasks involving non-diesel fuels, such as burning biomass,⁽⁵⁵⁾ and welding.⁽⁵⁶⁾ Close proximity to smoke plumes and welding activities occurred in less than 1% of the sampling time in this study.

Study strengths included the use of the wearable MA to capture task-based and peak exposures throughout the working day, repeated sampling on several farmers, minute-by-minute farmer activity logs by a trained observer, and the development of a calibration factor to convert BC concentrations to estimated EC concentrations. The MA was quiet and inconspicuous, facilitating sample collection. BC monitoring in this study occurred predominantly during busy harvest-days, but also included rainy days where few tasks were performed. This mix of harvest and non-harvest days was advantageous in characterizing farmers' daily exposures, as farmers' daily routines vary greatly. However, the small sample

size occurring over one season in one geographic area allowed us to evaluate only a few determinants of BC exposure; more monitoring across seasons and in other geographic areas are needed to evaluate determinants in greater detail. Furthermore, future studies that utilize advanced versions of the single wavelength MA used in this study – for example the AethLabs MA-series instruments that utilize multiple wavelengths – could provide a more robust analysis of particles in the ultraviolet PM (UVP) stage and apportion the source of BC, such as between diesel-exhaust, wood-smoke and other biomass burning.

Our chamber calibration results were consistent with other research that found a good linear relationship between aethalometer response and EC concentration.^(23, 57, 58) For example, Borak et al. found a strong linear association between a bench-top aethalometer and EC measured by NMAM 5040 ($r^2 = 0.91$).⁽⁵⁷⁾ However, the relationship between BC and EC can vary by location, source, season, detection method, and analytical method.^(5, 20–23) Our chamber calibration only extended to 20 $\mu\text{g}/\text{m}^3$ therefore we cannot be certain of the accuracy of the MA beyond that concentration.

Previous research has also shown that MA BC measurement artifacts (false positive and negative spikes) can occur during rapid changes in humidity and temperature, and from vibrations that dislodge particles adhering to the inlet tubing.^(24, 59) Cai et al.⁽²⁴⁾ found that a diffusion drier reduced humidity effects, wearing the instrument close to the body reduced temperature effects, and using size-selective inlets to remove large particles and periodically cleaning the instrument reduced vibration effects. In the environments sampled during this study, rapid changes in humidity rarely occurred. To reduce temperature and vibration effects, the MA was attached to straps in the upper center portion of the backpack between the shoulder blades to minimize movement and reduce inlet tubing length.^(60–65) Additionally, an optical effect, known as “shadowing” or “particle loading”, caused by a change in the light attenuated per unit mass of BC on a filter as more particles are deposited on the filter, has been shown to reduce MA accuracy.⁽⁶¹⁾ This effect reduces the MA reported BC concentrations on highly loaded filters compared to partially loaded filters. Several methods with varying degrees of complexity have been used to correct for this downward drift over time in MA readings.^(60, 61, 63, 64) Park et al. compensated for signal attenuation and derived adjusted BC concentrations 1.1–1.2 times greater than the raw BC data.⁽⁶³⁾ Because mean daily BC readings in this study were relatively low ($\text{AM} = 2.3 \mu\text{g}/\text{m}^3$, $\text{GM} = 0.5 \mu\text{g}/\text{m}^3$), correction factors for particle loading were not applied; however several measures were undertaken to minimize filter overloading. We used a sharp-cut size-selective inlet to remove larger, non-DPM particles ($> 2.5 \mu\text{m}$) from the airstream; the MA was operated at its lowest flow rate setting (50 ml/min) to reduce filter loading over time, and the filter strips were changed daily based on the manufacturer-recommended filter strip life span. While some light attenuation may still have occurred, we believe the effect was minimal.

CONCLUSIONS

Farmers in Iowa were frequently involved in activities involving diesel-fueled vehicles and equipment during the fall harvest season. Driving light and heavy-duty diesel-fueled vehicles was associated with the highest BC exposures in farmers, with BC concentrations similar to

those observed for urban vehicle-related occupations. Higher BC concentrations were observed for indoor bystander vs. outdoor bystander, for open cab vs. closed cab, and for near vs. far proximity to vehicles. To more fully characterize these exposures, further evaluations of other seasons and activities is warranted.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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FIGURE 1.

An example of daily task sequence and BC concentration ($\mu\text{g}/\text{m}^3$) per task.

FIGURE 2.
Probability plot of daily AM and GM (lognormal with a 95% CI) BC exposure distributions.

FIGURE 3.

Box plots of BC concentrations ($\mu\text{g}/\text{m}^3$) by activity and fuel type. The line within the box shows the median BC concentration, the box shows the inter-quartile range, the whiskers show $1.5\times$ nearest inter-quartile range, and the circles indicate outliers.

FIGURE 4.

Diesel chamber experiments, BC concentrations by microAeth compared to EC concentrations by *NMAM* 5040.

TABLE I.

Farmer activities by presence of specific fuel-type and corresponding sample duration, proportion of task 10 $\mu\text{g}/\text{m}^3$, and BC concentrations.

Activity	Diesel Present*	NI ¹	N2 ²	Sample Duration (min)			Median	Proportion of Task >=10 $\mu\text{g}/\text{m}^3$ (%)			BC ($\mu\text{g}/\text{m}^3$)		
				Median	25th %ile	75th %ile		25th %ile	75th %ile	AM	GM	GSD	Max
Transport Load	Other	7	2	23	10	32	0	0	0	0.6	0.4	3.3	1.6
Transport Load	Yes	7	4	14	11	20	5	0	53	7.8	3.6	4.8	15.9
	All	14	5	18	11	24	0	0	5	4.2	1.2	5.8	15.9
Animal Work	NA	12	6	4	2	6	0	0	0	1.1	0.4	5.1	6.0
Animal Work	Other	3	3	9	5	70	0	0	0	0.3	0.3	1.6	0.4
Animal Work	Yes	10	3	6	4	10	19	0	50	9.1	4.9	3.4	36.8
Animal Work	Unknown	3	2	8	2	12	0	0	0	1.0	0.8	2.5	1.6
	All	28	10	6	2	9	0	0	6	3.9	1.0	6.1	36.8
Drive	Other	17	6	6	3	10	0	0	0	1.1	0.4	3.7	11.7
Drive	Yes	37	12	5	4	9	0	0	11	12.3	1.3	8.3	288.4
Drive	Unknown	34	10	10	6	16	0	0	0	1.0	0.3	5.4	10.9
	All	88	16	7	4	13	0	0	0	5.8	0.6	6.9	288.4
Grain Bin	NA	6	4	8	5	14	0	0	0	0.6	0.3	4.3	1.7
Grain Bin	Other	6	2	9	5	18	0	0	0	1.1	0.8	2.3	2.7
Grain Bin	Yes	5	2	4	3	4	0	0	0	1.4	0.6	6.2	3.3
Grain Bin	Unknown	1	1	49	49	49	3	3	3	4.3	4.3	4.3	4.3
	All	18	5	6	4	14	0	0	0	1.2	0.6	4.1	4.3
Harvest	Yes	19	5	23	19	29	0	0	0	1.3	0.5	6.3	4.2
Light Misc. Farm	NA	39	14	9	6	15	0	0	0	2.8	0.5	5.9	29.5
Light Misc. Farm	Other	13	6	15	11	27	0	0	12	5.1	2.3	3.4	35.0
Light Misc. Farm	Yes	25	11	5	2	11	0	0	25	7.0	1.8	7.3	44.4
Light Misc. Farm	Unknown	13	6	5	2	9	0	0	0	1.7	0.5	7.2	9.3
	All	90	17	8	3	15	0	0	6	4.1	0.9	6.6	44.4

Activity	Diesel Present*	N1 ¹	N2 ²	Sample Duration (min)			Proportion of Task ≥10 µg/m ³ (%)			BC (µg/m ³)		
				Median	25th %ile	75th %ile	Median	25th %ile	75th %ile	AM	GM	Max
Load	Other	10	2	14	7	21	0	0	0	0.4	0.2	3.7
Load	Yes	47	12	5	3	18	0	0	25	5.7	1.6	47.2
	All	57	12	7	3	19	0	0	3	4.7	1.1	47.2
Other: Indoor	NA	29	15	26	11	50	0	0	0	0.6	0.2	4.5
Other: cutting concrete	NA	1	1	3	3	3	60	60	60	7.3	7.3	7.3
Other: cutting concrete	Other	2	1	23	16	30	51	34	68	37.5	24.7	65.7
	All	3	1	16	3	30	60	34	68	27.4	3.3	65.7
Transition*	NA	133	20	3	1	5	0	0	0	1.2	0.4	12.5
Vehicle Maintenance	NA	20	9	16	5	24	0	0	0	1.0	0.6	5.9
Vehicle Maintenance	Other	9	3	3	2	7	0	0	0	0.6	0.5	1.8
Vehicle Maintenance	Yes	26	16	5	3	12	0	0	3	6.2	0.9	74.7
Vehicle Maintenance	Unknown	1	1	3	3	3	0	0	0	0.0	0.0	0.0
	All	56	17	5	3	20	0	0	0	3.4	0.7	74.7

* Diesel present – fuel type categories include the following: NA = not applicable, Other = other fuel source (non-diesel), Diesel, or Unknown

¹ Sample size of unique task/fuel type/time window

² Number of measurement days

TABLE II.

Effect of farmer location and microenvironment on BC concentrations for the activities 'Light miscellaneous farm', 'Load', and 'Drive'.

Activity	Diesel vehicle	N ¹	Sample Duration (min)				Proportion of Task 10 µg/m ³ (%)				BC (µg/m ³)			
			Median	25th %ile	75th %ile		Median	25th %ile	75th %ile		AM	GM	GSD	Max
By Farmer location														
Light misc farm	Outside vehicle													
Light misc farm	Near	14	3	2	3		6	0	40		8.5	2.9	7.3	29.7
Light misc farm	Far	3	3	2	7		0	0	0		0.8	0.3	7.2	1.9
Light misc farm	In vehicle	18	6	2	15		4	0	41		10.4	2.1	9.2	53.0
Light misc farm	Indoor bystander	2	3	2	4		100	100	100		21.4	18.4	2.2	32.2
Light misc farm	Unknown	1	1	1	1		0	0	0		0.4	0.4		0.4
Load	Outside vehicle													
Load	Near	20	4	3	7		0	0	2		4.9	1.4	5.3	41.3
Load	Far	2	5	4	7		0	0	0		0.4	0.3	5.1	0.8
Load	In vehicle	49	4	3	11		0	0	12		5.5	1.5	5.8	47.2
By Microenvironment														
Drive	Other (includes in garage)	18	2	1	5		0	0	100		28.2	1.8	16.5	288.4
Drive	Open cab	19	4	1	5		0	0	7		5.9	2.1	4.3	41.8
Drive	Enclosed cab	16	6	4	10		0	0	0		1.3	0.4	6.8	5.2
Load	Other	29	4	2	6		0	0	0		4.0	1.3	4.8	41.3
Load	Open cab	25	4	2	6		0	0	40		9.6	3.2	6.5	47.2
Load	Enclosed cab	25	4	3	24		0	0	0		1.8	0.9	4.1	8.8

¹ Sample size of unique task/fuel type/time window