Smoke Exposure Among Wildland Firefighters

Prepared by:

Timothy E. Reinhardt, George Broyles, Joe Domitrovich, Roger D. Ottmar

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EXECUTIVE SUMMARY

This summarizes research into occupational exposures to smoke and dust among wildland firefighters, led by the USDA Forest Service (USFS), Technology & Development Center (NTDP) program between 2009 and 2012. For the first three years, firefighter exposures were the focus of sampling breathing zone exposures, beginning with only carbon monoxide (CO) in 2009, but extending to respirable particulate matter (PM4) and respirable crystalline silica (as quartz) beginning in 2010. The data were obtained in parts of the US that represent most USFS Regions and include:

- 50 firefighter shifts/60 calls for initial attack incidents,
- 417 firefighter shifts at project wildfires,
- 83 firefighter shifts at prescribed natural fires, and
- 83 firefighter shifts at prescribed burns.
- For 2012, such exposures were sampled among 31 fireline managers.

The data collection gathered substantial information about many factors that, together, influence occupational exposures among wildland firefighters. These included crew type, experience of the firefighter and their supervisor, work activity, fuel type and canopy percentage, fire behavior, flame length, wind speed and position relative to the fire, slope and position relative to the fire, USFS Region, and other variables. The data were gathered to determine whether exposures observed across the country were similar to results obtained in the western US in the 1990s, and to help determine factors or conditions that drive high occupational exposures to smoke and dust. By identifying these factors or conditions, management interventions might be developed to reduce exposures among the workforce.

Exposures versus occupational exposure limits

The NTDP project found that the firefighters work long hours, usually shifts exceed 10 hours and were typically 12-15 hours in duration, with 6-10 hours on the fireline. Only when responding on initial attack (averaging 4.4 hours) did crews spend fewer hours on the fireline. Because firefighters work long shifts, traditional 8-hour shift-average occupational exposure limits (OELs) such as the Permissible Exposure Limits (PELs) from the U.S. Dept. of Labor, Occupational Safety and Health Administration (OSHA), the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limits (RELs), and more recently-updated Threshold Limit Values (TLVs®) recommended by industrial hygienists must be adjusted downwards to account for the long shifts, and should also be adjusted downward further when in a 14-day on/2-day off extended deployment. The Short Term Exposure Limits (STELs) from many authoritative sources and the NIOSH Immediately

Dangerous to Life and Health (IDLH) levels do not require such adjustment, but all may need to consider the additive effects of exposure to multiple contaminants in smoke.

The exact adjustment will depend on the shift duration and deployment regime. As an example, simply-tailored adjustments based on the typical daily exposure duration data indicate the following estimated percentages of overexposure to smoke (CO and PM4) and respirable crystalline silica (quartz):

	Percent Above Interim Occupational Exposure Criteria (and 95 % Upper Confidence Limit)			
Fire Type/Resource (n)[1]	**CO 5-min. STEL (200 ppm)**	**CO Shift (16/25 ppm)[2]**	**Respirable PM4 Shift (0.7 mg/m^3)**	**Respirable Quartz Shift (0.057 mg/m^3)**
Initial Attack Firefighters (50/18)	2.6 (5.7)	2.5 (6.0)	0 (15)	28 (50)
Project Fire Firefighters (417/80)	8.3 (10)	8.4 (10)	22 (29)	10 (17)
Project Fire Managers (31/31)	0 (9.2)	0 (9.2)	3.3 (15)	0 (9.5)
Prescribed Natural Fire Firefighters (83/16)	0 (3.5)	7.2 (14)	6.3 (26)	0 (17)
Prescribed Burn Firefighters (83/15)	6.7 (11)	9.2 (14)	20 (44)	6.7 (28)

Notes:

[1] Number of CO samples/Number of PM4 & Quartz Samples

[2] 16 ppm for 13-hr wildfire shift, 25 ppm for 10-hr prescribed burning shift

Ideally, exposures should be controlled such that none of the exposures exceed OELs, with 95% certainty. The data above indicate that as firefighters become managers in their careers, their exposures are seldom over relevant occupational exposure limits. However, as firefighters, they are likely to exceed recommended typical CO exposure limits, PELs for respirable crystalline silica, and recommended occupational exposure limits for PM4.

Factors affecting short-term exposures to carbon monoxide

The factors determining the personal daily maximum short-term exposures (5-minute average) for the firefighters were tested in a multilevel mixed-effects linear model, where the day and crew provided a random grouping factor. Of the available factors tested for their influence on the maximum 5-minute exposure, only the crew type, the work activity, and the wind speed and its interaction with work activity were significant predictors. Other factors may matter but the data were not complete enough to test them. As for crew type, the highest average 5-minute maximum CO exposures were for Type II(Fuels) and Type II(IA) crews. They were not significantly higher than Engine(VI) crews. The 5-minute CO exposures among the Type I/I(IHC) crews weren't significantly lower than the Type II crews. The 5-minute CO exposures among Type I and Type II crews were both significantly higher than dozer crews. The 5-minute maximum CO exposures among dozer and engine crews were not significantly different. Based on these data, Type II and Type I crews, and Engine(VI) crews should be the focus of peak exposure reduction.

Of the work activities, the highest average maximum 5-minute CO exposures occurred during dozer operations (all during initial attack), but these were not significantly higher than among those performing typical handline/sawyer activities. They were significantly higher than among pump operations, and ancillary tasks like hiking, briefings, breaks and during standby. Handline/sawyer (direct line construction) had average 5-minute maximum CO exposures that were higher than lighting, mop up, and pump operations, but they were not significantly higher than during holding operations. Windspeed had a very significantly positive effect on exposures among dozer operators, and a slightly positive effect among personnel holding and lighting. The factor analysis data indicate that peak exposure interventions might be most effective among initial attack dozer operations, handline/sawyer activities, and while holding firelines.

Factors affecting fireline-average exposures to carbon monoxide, respirable particulate, and respirable crystalline silica

A multilevel mixed-effects model using day and crew as a grouping factor was developed. Many promising factors (such as fuel model, wind speed, and fire behavior) had to be dropped due to missing observations. The final model retaining the most observations found that the crew type, the activity representing most of the fireline time and the amount of time it represented, and the position up or downwind of the fire were significant determinants of CO exposure. For fireline-average CO exposure, being mainly downwind of the fire obviously leads to significantly higher exposures vs. upwind. Among the crew types, the Type II(Fuels) and Type II(IA) crews had the highest fireline-average CO exposures, significantly higher than Engine(III/IV) and Dozer(I/II/III) crews, and Type II(Fuels) was even significantly higher than Type I/I(IHC). Fireline-average CO exposures among Type II(IA) crews were also higher than I/I(IHC) but not significantly so.

Among the activities that made up most of the time on the fireline, those performing Handline/sawyer(direct) tasks had significantly higher CO exposures than those doing mainly lighting tasks (lighting and lighting boss), pump operations and mop up. Exposures among those mainly holding fireline were significantly higher than those doing the lighting tasks, and those doing mop up. As might be expected, when ancillary tasks predominated (hiking, standby/staging, briefing), exposures were low. The fireline-average CO data indicate that management interventions will be most effective if focused on Type II and Type I/I(IHC) crews, especially when they are performing direct handline/sawyer assignments and holding fireline, and unavoidably downwind of the fire.

For PM4 and respirable quartz data, downwind positions had significantly higher fireline-average PM4 exposures than upwind positions. Fireline-average PM4 exposure was significantly higher among Type II(Fuels) and Type I/I(IHC) crews than among Engine(III/IV) crews. Although Type II(Fuels) crews had higher PM4 exposures than Type II(IA) and Type I/I(IHC) crews, they were not significantly higher. The PM4 exposures among Dozer(I/II/III) crews were higher than all crew types except Type II(Fuels) but were not significantly higher than any other crew type.

In terms of main activity during the shift, PM4 exposures among those doing mainly mop up were significantly higher than those doing mainly Handline/sawyer(Indirect) line construction, and those performing ancillary tasks. PM4 exposures for those doing mainly mop-up and holding fireline were also higher than Handline/sawyer(direct or indirect), and dozer operations, but not significantly so. The average PM4 exposures for those doing mainly mop up was higher, but not significantly higher than those holding firelines. PM4 exposure management implications from these findings indicate that the most effective opportunities to reduce PM4 exposures would be among Type II and Type I crews downwind of the fire, doing mop up and holding firelines. Dozer crews also present opportunities to reduce PM4 exposures.

For respirable quartz, the majority activity and the proportion of time it represented were the only significant factors. Those doing mainly dozer operations had higher respirable quartz exposures than all other tasks, but significantly higher than only holding, lighting and ancillary operations. Mop-up respirable quartz exposures were significantly higher than those doing mainly holding or lighting. Differences in these patterns for respirable quartz versus PM4 make sense when considering the source—respirable quartz arising only from soil disturbance, and PM4 representing mainly smoke. Management implications for respirable quartz are that dozer operations and mop up tasks present the best opportunities to control dust exposures.

Carbon Monoxide as an Indicator Pollutant

Linear regression results indicate that CO measurement is a reasonably useful real-time gauge of the inhalation hazard from smoke-derived PM4. Especially for tasks such as holding line, where almost all the CO and PM4 are due to the fire, the CO to adjusted PM4 exposure relationship is a valuable estimator of how much of the PM4 is due to fire emissions. When tasks generate soil dust, the total PM4 exposure will reflect the additional respirable portion of the dust created by these tasks (such as mop up, handline construction, bulldozer operations, hiking in dusty conditions, and driving on dusty roads). With the recent reduction of the OSHA respirable crystalline silica standard to 0.05 µg/m^3, attention to that soil dust hazard is warranted where soils contain quartz or other forms of crystalline silica. But for estimating exposure to fire-derived PM4, these data show a reasonably strong relationship over all USFS regions and during most tasks.

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1.0 INTRODUCTION

The USDA Forest Service, National Technology & Development Program (NTDP) collected breathing zone measurements of occupational exposure to smoke and dust at wildland fire activities across the U.S. between 2009 and 2012. This portion of the report presents the methods and results of the initial comprehensive analysis of these data. From 2009-2011, a variety of wildland fire crew types were included in the exposure monitoring program. In 2012, only line management staff were selected for exposure monitoring at a variety of wildfires.

Wildland fires can be summarized by the objective of the fire management activity. Fire Type is a convenient subdivision of the exposure data, because it translates readily to operationally meaningful descriptions of wildland fire management activities. The four basic fire types at which data were obtained by NDTP were:

- Prescribed Burns—intentionally-ignited burns of designated areas to achieve land management objectives, these are commonly bounded by pre-established firelines, roads and natural features, may have extensive hose lays to provide water along the firelines which are usually manned to prevent escape of the fire, and are ignited by ground-based personnel or aerial incendiary devices. Pile burning is a specific type of prescribed burning that involves ignition of machine-or hand-piled forest debris, left over one or more winters to cure, and typically covered during that time.

- Prescribed Natural Fires—these are naturally-ignited wildland fires that are allowed to continue to burn because they are achieving land management objectives. In that sense they are prescribed fires, and like prescribed burns the fires may require fire suppression intervention to stop their progress when they approach the boundary of the intended burn area. However, they do not benefit from the completely planned nature of prescribed burn ignition and firing rate management. Because the pattern and rate of ignition is not managed to a set plan like a prescribed burn, the ad hoc nature of the fire progress forces firefighters to engage in suppression efforts that are similar to wildfires.

- Initial Attack—these types of fires are characterized by the suppression efforts begun as soon as a wildfire is reported and accessible. The fire may be put out quickly with the initially-responding resources. The shift may include substantial time spent doing unexposed tasks while waiting for a fire to occur.

- Project Wildfires—When initial attack efforts fail, the fire typically expands in size with every day, requiring more personnel, resources and time to contain. Project fires can last over a month, and have a management and logistical support team operating out of a fire camp, often supplemented by rudimentary spike camps if terrain and logistics make end of shift return to a central fire camp infeasible.

1.1 SAMPLING METHODS

The 2009 data consisted of personal measurements of exposure to carbon monoxide (CO), measured using CO dosimeters (MSA Altair Pro) consistent with Method 6604, published by the National Institute for Occupational Safety and Health (NIOSH).[1] Beginning in 2010, data were also collected for exposure to respirable particulate matter (PM4) with a median diameter of 4 micrometers (µm), generally consistent with NIOSH Method 0600[2], with analysis of crystalline silica content using NIOSH Method 7500.[3] Pre-weighed 37-millimeter diameter PVC filters with 1 µm pore size in 3-piece cassettes were obtained from a commercial laboratory accredited by AIHA in the Industrial Hygiene Laboratory Accreditation Program (RJ Lee Group, Monroeville, PA). SKC Airchek pumps were used at a target flow rate of just over 1 liter per minute. The cyclone selected for the PM4 sampling was the BGI SCC1.062 (Triplex), constructed of aluminum to minimize wall losses from electrostatic effects. Because significant nonrespirable dust was expected at wildland fire events, and long shifts were expected, a relatively low sampling flowrate was desirable to minimize overloading filters. The Triplex sampler obtains a PM4 curve approximation at only 1.05 liters per minute, half that of alternative samplers, and according to manufacturer literature achieves a reasonably good match to the consensus sampling efficiency curve for respirable particulate established by the International Standards Organization, the European Standards Committee, and the American Conference of Governmental Industrial Hygienists (ACGIH).[4]

Field protocols were developed to provide a rich data set that could be used to analyze exposure against a variety of variables. As a result, data collection forms were designed to gather numerous environmental variables. Several different pocket-sized forms were used for specific data needs (Fig. A-1), and Form 7 was completed each hour to account for changes in the environment and crew activities. The protocols were also designed so that the data being collected can be used to supplement and corroborate the data from earlier studies which identified some key activity and environmental variables that appeared to drive smoke exposure.

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[1] Woodfin, W.J., in Ashley, K., and P.F. O'Connor, Editors. National Institute for Occupational Safety and Health, NIOSH Manual of Analytical Methods (NMAM), Fourth Edition. Carbon Monoxide: Method 6604, Issue 1. Atlanta, GA. May 1996.

[2] Bartley, D.L., in NMAM, Fourth Edition. Particulates Not Otherwise Regulated, Respirable: Method 0600, Issue 3. January 1998.

[3] Key-Schwartz, R., Ramsey, D. and Schlecht, P., in NMAM, Fourth Edition. Silica, Crystalline, By XRD (filter redeposition): Method 7500, Issue 4. March 2003.

[4] American Conference of Governmental Industrial Hygienists (ACGIH). Appendix C: Particle size-selective sampling criteria for airborne particulate matter. In: 2015 TLVs® and BEIs®. ACGIH, Cincinnati, OH. 2015.

NTDP observation crews were trained in the use and maintenance of the sampling equipment as well as the protocols. Prior to actual field work, the project leader met with numerous fire managers and others to inform them of the project and the need for access to fire crews during incident operations. The project leader also worked with the National Interagency Coordination Center (NICC) and the Geographic Area Coordination Centers (GACC) to establish resource ordering protocols for NTDP field observers. The project leader met with the national Area Commanders and Type I Incident Commanders during the preseason. This preseason work facilitated the initiation of resource orders and expectations between the Incident Management Teams and NTDP were agreed upon. When a candidate fire was identified, the project leader would contact the IMT, or in the case of prescribed fires, the Fire Management Officer to ask for permission to work that incident. After receiving approval from the appropriate individual a resource order would be initiated by the GACC and NTDP observers would travel to the incident.

At the incident, the NTDP observers, working with incident personnel would identify an appropriate crew for observation. Because NTDP had been working on a project to update the fireline production rates for crews, the smoke exposure project was incorporated into that project during the first field season of 2009. Consequently the smoke monitoring on suppression fires during 2009 was focused on crews that were engaged in direct or indirect line construction efforts. The project and data collection methods would be explained to the crew and three volunteers on the handcrew would be asked to wear a dosimeter for the shift. NTDP observers would begin recording and monitoring crew activities at the beginning of each shift. On wildland fires this was typically at the morning Operational briefing at 0600. The crew would be observed until they returned to the Incident Command Post or spike camp. If the crew line spiked, NTDP observers would also remain on the line for the night. By remaining with the crew throughout the entire shift, we could assure the accuracy of the data and account for any factors that may influence smoke exposure levels. During the shift the hourly forms would be completed, digital images were taken and GPS data was collected. NTDP observers did not attempt to influence the crews’ work practices.

At most wildfire events, an extra CO dosimeter and PM4 sampling train were left in a central location of the incident command post, or at a spike camp that the crew was assigned to. They were primarily intended to be started upon initial visit to the camp and ended every 24 hours. These samplers were left unsupervised but otherwise handled in the same way as the personal exposure samples. Because the study had only personal sampling equipment and methods designed for occupational exposures, which are not as sensitive as the methods required for assessing public health hazards, it is likely that the statistical metrics for these “camp” results were biased by the detection limit censoring, and so indicate higher exposures than actually occurred.

The CO dosimeters were activated at the beginning of each shift (typically at 0600 on fires) and removed from the crew prior to their departure back to the incident command post because there was no smoke exposure at the Incident Command Posts the crews were working at during the observed fires. The dosimeters were programmed to record the average and peak CO concentration every minute. The average value was used for analysis. The dosimeters have three alarms, a vibrating alarm, blinking LEDs and an audible alarm. During data collection, the vibrating and audible alarms were disabled to minimize firefighter distractions. The LED alarm was set to 200 PPM so that it was seldom activated during suppression activities.

The filter flow rates through the PM4 samplers were calibrated on site with a primary standard frictionless piston (BIOS DC-Lite) before sampling, and checked again after sampling, using the calibration adapter provided by the manufacturer. Grit pots were checked and emptied of nonrespirable dust at least once daily, and the amount of debris was estimated in terms of standard 325 mg “aspirins” at the time of the servicing.

After sampling, all filters were capped and transported under chain of custody to the laboratory, accompanied by field blanks prepared each day. CO dosimeters were bump-tested at the end of each shift, and the data downloaded to field computers before the instruments were reset.

1.2 DATA REDUCTION

Because CO data was collected on a minute by minute basis during operational shifts it is possible to calculate several different occupational exposure metrics to evaluate the exposure to acute toxins as well as those that accumulate over longer periods. Spreadsheets that had been developed for the fireline rate construction project were modified and expanded to automatically calculate the following metrics:

- The highest 1-minute CO exposure value provides the peak exposure level for each firefighter on every shift. This is a good value to compare against the NIOSH IDLH standard of 1200 ppm.
- The highest 5-minute CO exposure value was obtained by rolling average through each firefighter’s shift, incrementing each minute of the day. This metric is a good value to compare against the typical state-jurisdiction (e.g., California and Washington) STEL of 200 ppm.
- Eight-hour CO exposures were also calculated for each firefighter. A rolling eight-hour exposure was calculated (incrementing forward in time with each minute of monitoring data), and the highest value was automatically selected for comparison to 8-hour duration OELs. When the firefighter was on the line for less than eight hours the eight-hour exposure was calculated by adding the appropriate amount of time at zero exposure to the time at the measured fireline exposure, so the calculation can be made on an eight hour exposure. In these cases, field notes were consulted to confirm that no known exposure took place during the additional time in the eight

hours, and an 8-hour time-weighted average (TWA) was calculated. A convenient metric for this is the TLV of 25 ppm that should be health-conservative for healthy workers, even when firefighting occurs at high elevation. A suggested effort would be to confirm this assumption through application of one of the pharmacokinetic models to predict COHb from exposure conditions.

- Fireline exposures were also calculated to represent the TWA exposure during all time on the fireline. Because the dosimeters were measuring CO the entire time these firefighters were on the fireline, it is a direct measurement for these data. The PM4 and respirable crystalline silica samples began and ended with the fireline time, and therefore these only represent exposure during activities on the fireline. If the time on the fireline is more than eight hours, a variety of methods are available to adjust an 8-hour OEL downward to account for the longer time.
- Shift exposures were also determined for each firefighter by using the total exposure during fireline operations and adding the total shift time to the calculations. The shift exposure is a TWA that includes exposure (or zero exposure) off the fireline. If fire camp data had shown that the firefighters were in an inversion and were exposed even though they were not on the fireline, this would be included in the shift average. However, the fire camp measurements indicated uniformly there was no appreciable CO exposure off the fireline at these events, so the TWA uses zero ppm CO for this unexposed time in the TWA formula.

After initial work up in the summary spreadsheets, the data were exported to the R System for Statistical Computing. Because a significant proportion of the CO observations were nondetect for many hours of each day, ½ the detection limit (1 ppm) was used for such observations after Hornung and Reed, because the data were in general highly skewed, with geometric standard deviations above 3.0.[5] The detection limit for the PM4 and respirable crystalline silica measurements depended on the length of the sample in addition to the underlying laboratory reporting limits. Those results which were reported as below the detection limit were also censored to ½ the detection limit. Summary statistics were calculated using the package STAND Version 2.0, which applies the Kaplan-Meier nonparametric methods for subsets which include data that are censored by the detection limit, and otherwise uses the methods recommended by the AIHA in Exposure Assessment Strategy (Ignacio and Bullock, 2006).[6] Data were generally best described by or assumed to follow a lognormal distribution.

1.3 EXPLANATORY VARIABLES

The field data collection attempted to collect detailed data for a wide variety of potentially explanatory variables. Fire type has already been introduced. Others are summarized here.

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[5] Hornung, R.W., and L.D. Reed. Estimation of Average Concentration in the Presence of Nondetectable Values. Applied Occupational and Environmental Hygiene 5(1):46-51, 1990.

[6] Ignacio, J. S. and W. H. Bullock, *A Strategy for Assessing and Managing Occupational Exposures*, Third Edition, AIHA Press, Fairfax, VA 2006.

Where variables were coded specifically into new variables during the data analyses, these decisions are explained here.

1.3.1 Fire Management and Crews

A typical career path for firefighting personnel involves progression from crew personnel of various types to leadership roles. As they move up the leadership ranks, management personnel have substantially different duties than the crews do. For example, depending on the size and duration of the incident, supervisory personnel above the crew level are likely to be assigned responsibility for sectors, divisions, and other specific roles within the incident management team. In these roles, they are often required to be mobile, using extensive hiking, vehicles, and aircraft to gain a bigger-picture view of the fire situation and direct the crews and other tactical and logistical support resources. Because fire managers are likely to have longer careers in fire than crew members, the project measured exposure only among fire managers in 2012, to assess whether there was a difference in exposure over the longer portion of the fire managers' careers than in their early days as firefighters.

1.3.2 Crew Types

The 20-person handcrew with superintendent is a mainstay of the fire workforce represented in these data, but there were many other types of fireline personnel represented. Wildland fire crew types in this project included those that represent the most highly-trained, fit and experienced hand crews (Type I Interagency Hotshot Crews, or IHC), and those consisting of forest and range personnel who may have much less experience (Type II crews) or who have significant fire experience but primarily perform prescribed burning (Fuels crews). Some Type II crews are trained and qualified for initial attack, they are designated Type II(IA). Then there are many types of fire engine-based crews, typically ranging from two to five personnel per engine. Engine types represented in this data include structural fire engines (represented by Type II Engines), and a variety of wildland engines (represented by Type III, Type IV and Type VI Engines).

Bulldozer and tractor/plow combinations were represented by Type I, Type II and Type III dozers, which included an operator, and an accompanying dozer boss moving primarily on foot. No helitack or smokejumper crews were represented in these data.

1.3.3 Work Activities

There are many specific tasks performed by firefighters, some are common and others would be dependent on the operational needs for the incident and the equipment in use. The field data collection recorded dozens of unique activities; these are explained further in the following subsections. There are also ancillary activities that are common to every incident, which mostly would not be associated with exposure to smoke. These include briefings, breaks and a variety of standby time, when fire personnel are waiting for decisions to be made, logistical support or other actions to occur, or coordinating with other resources. There is also transportation by vehicle or aircraft, almost always a task occurring at the start and end of a shift, usually accompanied by hiking to and from a road or other drop point to the deployment assignment. These transportation activities can consume anywhere from zero to many hours in a day. Fireline time occasionally included ancillary transportation tasks (hiking or driving from one assignment to another) during the block of time that made up the fireline time from start to end of daily deployment at the fire. Travel time after the fireline time ended was generally not monitored for smoke exposure.

Most of the ancillary tasks are not exposed to significant smoke, but as this project found, personnel can be exposed to engine exhaust and road, trail or fire camp dust while engaged in them. For purposes of analyzing which factors contributed to smoke exposure, such activities originally described as “Briefing”, “Driving”, “Hiking”, “Standby” and “Other” (as the variable “*Activity*”) were combined into one level “Ancillary” of the consolidated factor “Activity2”.

1.3.3.1 Fireline Construction Tasks

Construction of fireline can occur using mechanized means such as the tractor-plow or bulldozer, which is most widely used on gentle terrain. On steeper terrain and when mechanized resources are not available, hand crews dominate fireline construction. In certain conditions, fireline explosives are also used, but personnel involved with fireline explosives were not sampled during this project. Two types of fireline construction are defined: direct and indirect. Direct fireline construction is at or closely along the edge of the existing burning fire. Indirect fireline is at a location farther from the actively burning fire, sometimes substantially distant. The hand crews are typically assigned to specific tools, and include one or more sawyers who operate chainsaws to cut up large woody fuels and drop hazard trees, and swampers who manipulate interfering brush to assist the sawyer and move the cut pieces out of the way. Lighting a smaller fire in a “burnout” to eliminate unburned fuels between the active wildfire and a defensible perimeter is a routine task that is commonly done by hand, but may use ATVs, and aircraft in some circumstances. Lighting is most commonly done using drip torches or fusees.

Because there were relatively few instances of some tasks, allied tasks were grouped to improve modeling power. For purposes of analyzing which factors contributed to smoke exposure, the direct fireline construction activities originally coded in the variable “Activity” as “Handline Sawyer(Dir)”, “Handline(Dir)”, and “Scouting.Direct” were combined into one level “Handline/Saw(Dir)” of the factor “Activity2”. Likewise, indirect fireline construction activities “Handline Sawyer(Ind)” and “Handline(Ind)” were combined into one level “Handline/Saw(Ind)”.

Both “Dozer” and “Dozer Boss” were grouped into one Activity2 level “DozerOps”. Finally, the activity “Lighting” was combined with “Lighting Boss” into one Activity2 level “LightingOps”.

1.3.3.2 Fireline Defense Tasks

These tasks include “holding”, which involves taking a position along a section of fireline and actively smothering embers and rolling seed cones and other objects which cross or threaten the fireline. Another fireline defense task is “gridding” which involves patrolling up to several hundred feet away from the defined fireline in a search for spot-fires and burning embers that may lie outside the fireline.

1.3.3.3 Post-Flaming Phase Tasks

Mop up occurs after the main flaming phase of a fire is over. It involves extinguishing pockets of flaming and smoldering forest fuels within the fire perimeter. Mop up can be broadly categorized as wet or dry. Wet mop up has accessible water from wildland fire engines, portable tanks or surface water impoundments. Dry mop up uses only native soil to cool smoldering pockets of burning biomass. For analysis, both types were combined into one “mop up” category in the factor “*Activity2*”. If water hose lays are available, the firefighter sprays smoldering fuels with water, scraping burning coals apart and mixing with soil and water to extinguish them. If water is not available, the firefighter exposes smoldering fuels using hand tools, and applies dirt with a shovel to smother the combustion. During this task, the firefighter also disturbs the inorganic ash left from fire-consumed fuels, though the ash is expected to be much less toxic than fresh aerosol from active fire emissions

1.3.3.4 Prescribed Burning Tasks

Lighting and holding are the two main activities that occur at prescribed burns, followed by mop up. Lighting at the prescribed burns in the study was by manual drip torch. Lighting at one fire on the DeSoto National Forest had some ignition done with aerial incendiary devices (the plastic sphere dispensers known as “ping pong balls”).

1.3.4 Environmental Conditions

The environment that firefighting activities occurs in can be described by many variables of the terrain, the landscape (biomass) fuels that are burning, and the weather. These in turn influence the fire behavior, and because the fire behavior is the primary determinant of emission composition and whether the smoke plume is strongly or weakly buoyant, several key fire behavior variables were examined for their effects on exposure.

1.3.4.1 Fuel Model

The fuel model (visual estimate) was considered for effects on smoke exposure. Fuel model observations were collected in the field based on the 13 National Forest Fire Laboratory (NFFL) categories developed by Albini and Anderson.[7] Many of the individual observations were a combination of two or even three fuel models, leading to over-parameterization. To attempt to preserve a favorable ratio of observations to factors and levels, the number of levels of these NFFL fuel models were reduced by combining categories, generally based on total fuel load and rate of spread:

- Grass, grass/brush, and grass/timber were combined into a single category "*light*";
- Brush, grass/brush/timber were combined into a single category "*moderate*"; and
- Brush/Timber, timber, and slash were combined into a single category "*heavy*".

1.3.4.2 Slope and Slope Position

The slope (in percent) was intended to be observed hourly (as a visual estimate) for the subject firefighters, and the firefighter's position on that slope relative to the fire was recorded. If the firefighter was uphill of the actively burning area closest to the firefighter, their position was 'uphill'.

1.3.4.3 Wind Speed and Wind Position

The wind speed at observer height above ground level, in miles per hour (mph), was intended to be observed hourly (using a Kestrel Model 4000 Weather Meter) for the subject firefighters, and the firefighter's position relative to the fire was recorded. If the firefighter was upwind of the actively burning area closest to the firefighter, their position was 'upwind'.

1.3.4.4 Temperature

The temperature (in degrees Fahrenheit) was intended to be observed hourly (with the Kestrel) for the subject firefighters.

1.3.4.5 Relative Humidity

The relative humidity (in percent) was intended to be observed hourly (with the Kestrel) for the subject firefighters.

1.3.4.6 Fire Behavior

Fire behavior was intended to be observed at least hourly during data collection. To increase the ratio of the number of observations to the number of types of fire behavior, field observations were lumped into four categories:

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[7] Anderson, Hal E. Aids to Determining Fuel Models for Estimating Fire Behavior." USDA Forest Service. General Technical Report INT-122. 1982.

- *“Smoldering”*;
- Observations categorized as “*Surface-smoldering*”
- What had been called “ground” in 2009, and “surface” in later years were combined into a single category “*Surface*”; and
- Crowning, spotting, and torching were combined into a single category “*Active*”.

1.3.4.7 Flame Height

Flame height (flame length) was observed at the same time as fire behavior.

1.3.4.8 Inversion

Whether or not an atmospheric inversion was present in the area of the crew was intended to be observed at least hourly during data collection. The inversion factor had two levels, yes or no.

1.3.4.9 Canopy

The percentage of overhead canopy in the area of the crew was intended to be observed at least hourly during data collection. Numerical estimates were combined into three levels (<33%, 33-66%, and 66-100%).

1.3.5 Region, State and Land Ownership

The Forest Service Region (1-10) was recorded for each fire, as was state and in most cases, land ownership (federal, state or private).

1.4 DATA MODELING

Because of the variability in smoke exposures, modeling was undertaken to analyze the source of variability and improve understanding of the factors that determine smoke exposure. For the following exposure response variables, the analyses were performed on the log of the exposure because each distribution approximated a lognormal distribution:

- 5-minute maximum CO exposure (a representation of a STEL exposure situation),
- Fireline-average CO exposure,
- Fireline-average PM4 exposure, and
- Fireline-average respirable crystalline silica (quartz) exposure.

General modeling approaches and tests are summarized here. Unique aspects of modeling for specific response variables are discussed in the corresponding results sections below. Explanatory factors for peak 1-minute exposures were not modeled, and explanatory factors for shift-average exposures were not modeled because they were expected to depend strongly on the amount of non-fireline time within the workshift, which was in turn a function of distance and available travel modes (driving or hiking) between the fire and the base of operations of the firefighters (fire camp, spike camp or ranger station/work center). Unless traveling in vehicles that exposed firefighters to road dust and exhaust, exposures would be zero during these periods. These factors would also not be useful explanatory variables of exposure, other than to confirm that shift-average exposures are lower by the percentage of time spent off the firelines.

The exposures of fire managers were summarized separately from firefighters, and other than indicating an apparently lower average exposure, a model for their exposures has not yet been developed. For the firefighters, the data structure of the observational data set was considered and hierarchical “multilevel” mixed-effects models (MLMs) were developed and fit to the observed exposures.[8] In the resulting hierarchical structure of the MLM, the individual “firefighter” was omitted as a clustering factor because there were relatively few replicates by firefighter (specifically, the firefighters were unique for 70% of the 621 shifts. Of the remainder, 72 firefighters were monitored on two days, and 14 were monitored on 3 or more incidents. Although omitting the individual firefighter as a clustering variable may introduce bias through the lack of independence of random effects of an individual worker, the data were not obtained in a way that was structured to examine the effect of the individual. Statistician advice indicated that the proportion of repeated measures on individuals and risk of bias was small in comparison to the loss of degrees of freedom incurred by structuring the hierarchy to add the individual effect.

Because crews are deployed as teams and were almost always assigned to tasks as a group, with close areal proximity within the group being the norm rather than the exception, the crew was a natural grouping factor. And because a given day presents a unique set of environmental conditions in terms of incident type, weather, general incident behavior and so forth, the day was another factor influencing the exposure for the crew. On each day of exposure monitoring, 2-3 firefighters were typically monitored from within each of two crews. The crews containing the instrumented firefighters were often assigned to different areas of the fire, resulting in usually 4-6 firefighters per day from among two crews. At four prescribed burns, 6-9 firefighters were monitored from just one crew. The grouping factor selected was for any given day a combination of the day and crew variables (factor “daycrew”). As such, our conception is that it captures the random effects of the environmental and site conditions of the day, as well as the unique assignment and characteristics of the crew, if more than one crew was observed that day. This random “daycrew” factor was a random clustering factor which averaged zero in the model, but accounted for each fire being a unique combination of environmental and individual

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[8] Finch, W.H., J.E. Bolin, and K. Kelley. Multilevel Modeling Using R. Chapman & Hall/CRC Press. Boca Raton, FL 2014.

crew characteristics, and of course is simply a sample from a larger population of crews and daily conditions and sites that will continually increase.

Alternative grouping factors were explored (Crew within Day within Fire Name, for example, since there were many instances of multiple days at a given named project fire), but in these data, daycrew effectively captured cluster variation as it had the largest intraclass correlation (ICC) of the alternatives explored. For these reasons, two-level MLMs were developed for the analyses, where fixed effects of explanatory variables were tested after grouping by the daycrew factor. A null model using the daycrew factor was developed, and the significance of the MLMs were compared using analysis of variance (ANOVA). We developed only a random-intercept model, which utilized the same average slope for each fixed effect across all instances of "daycrew", because different slopes for each level of the daycrew factor would not be useful for predicting future exposures. All data analysis was performed in the R System for Statistical Computing.[9] The R packages NLME and LME4 were used for most of the data analyses. The R package lmerTest was used for model simplification. Parameter estimates for a given model used restricted maximum likelihood (REML) estimates to reduce potential bias.[10] The significance of fixed effect parameters was tested using both Satterthwaite and Kenward-Roger degrees of freedom approximations in LME4 and lmerTest. Model fits were evaluated using:

- QQ plots of residuals,
- Plots of residuals versus fitted—overall and scaled by fixed effect category to confirm that they were relatively homogenous,
- Plots of observed versus fitted—overall and by fixed effect category.

Overall model comparisons via ANOVA were performed after refitting the models using maximum likelihood estimates of fixed effects, per current guidance. Continuous variables (windspeed, slope, and percentage of fireline time represented by a given activity) were tested using grand mean centering to reduce collinearity effects and aid interpretation (Finch, Bolin and Kelley, pg. 34). Graphics were mainly produced in the package Lattice.[11]

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[9] R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/

[10] Maindonald, J., and J. Braun. Data Analysis and Graphics Using R. An Example-Based Approach. Second Edition. Cambridge University Press, New York, NY, 2007.

[11] Sarkar, D. Lattice: Multivariate Data Visualization with R. Springer Science+Business Media, New York, NY 2008.

1.5 INTERPOLLUTANT CORRELATION MODELING

Excel master files of data for each crew and day were queried for the PM4 and respirable crystalline silica data (all found to be only as quartz) which was measured among a subset of 119 firefighters and fire managers participating in the CO exposure monitoring. These PM4 and quartz data covered essentially the entire time the firefighters were on the fireline. The time-matched CO data were paired with these data. Any changes in work activity observed within the fireline data were quantified and the various work activities were given a weighting representing how much of each firefighter's time on the fireline that they represented. The task with the largest percentage was selected as the main task on the fireline that day. It represented between 18.5% and 100% of the fireline time, thus it was an imperfect categorical metric but the only option given the lack of task-based PM4 exposure data.

Two key issues in the data could mask a true correlation between PM4 and CO in smoke. These included:

1. Low-concentration data for either PM4 or CO. This is because results become much less precise as they approach the method detection limit, reducing their utility due to proportionately higher measurement error; and
2. Respirable particulate matter that was from soils, not smoke.

Our data analysis strategy tried to minimize these sources of error. To reduce the error from measurement uncertainty, we dropped those sample pairs of CO and PM4 results that were either less than 1.2 ppm CO, or below the laboratory reporting limit for PM4.

Background context to this analysis is the fact that wildland firefighting is frequently a dusty job, not just a smoky one. Fire site conditions are usually dry and can be windy, causing exposure among firefighters to airborne soil-derived dust created by soil disturbance that is common during certain firefighting activities. Typically dusty activities include:

- Vehicle transportation when it occurs on dirt and gravel roads, often in convoys (an ancillary activity classified as "Driving" for this interpollutant correlation analysis);
- Hiking on trails, firelines and across country, usually in linear formations (an ancillary activity classified as "Hiking" for this analysis;
- Standing by for orders or logistical considerations at staging locations, which can be adjacent to heavily-trafficked roads and incident command/logistics posts (an ancillary activity classified as "Standby" for this analysis);
- Digging and improving firelines near burning or burned out fuels "Handline(Direct)", or further away from the fire at defensible locations "Handline(Indirect)"; and

- Operating bulldozers and tractor-plow combinations (“Dozer”) or closely supervising on foot (“Dozer Boss”) the grading of firelines; and
- Performing “Mop up” activity.

Though soil-derived dusts from such activities should mainly be larger than the PM4 cutpoint, a significant fraction are likely to pass through the size-separation devices (usually a cyclone) used to segregate respirable from inhalable particulate matter. Because the correlation of CO and PM4 in smoke was expected to be obscured when PM4 exposure was mainly due to soil dusts, the exposure data from these activities were checked for samples likely to represent a significant amount of dust, rather than mainly smoke. A consistent method of achieving this was by using the respirable quartz data from the PM4 samples.

Of the 119 samples of PM4 available for evaluating a correlation with CO, 43 were dropped because the CO concentration was below 1.2 ppm. Of the remaining 76, 32% had no detectable respirable quartz. Using the R package STAND to describe such censored distribution, the Kaplan-Meier estimated mean quartz percentage of the 76 PM4 samples was 5.6%. We calculated a quartz-adjusted PM4 concentration (for those samples with detectable quartz) by subtracting the quartz concentration from the total PM4 concentration. We then plotted the adjusted PM4 concentration against the paired CO concentrations to examine the relationship among the 76 pairs of data.

2.0 RESULTS AND DISCUSSION

In all, monitoring was completed for 83 person-days at prescribed burns, 83 at prescribed natural fires, 50 at days with initial attack deployments (within which 60 total events occurred) and 417 person-days were monitoring at multi-day project wildfires. In 2012, data were only collected from wildland fire management personnel who had supervisory duties at wildland fire operations. Thirty-one shifts of fire operations supervisors were monitored in that year, all were deployed within sectors of wildfires, spending little time in fire camps.

2.0.1 Work Durations

When compared to traditional workplaces, wildland firefighters typically work much longer hours. National Wildfire Coordinating Group (NWCG) and federal agency policy limits firefighters to 14 days on assignment without a mandatory 2-day break. Fireline time is the duration of time on the fireline, which was frequently less than the entire work shift. For initial attack days, the fireline time was the sum of hours at each fire when there were multiple events in a day. During their work shift time away from the fireline (in transit or staging) firefighters were usually unexposed to smoke, though this may not always be true at project fires, especially when they are accompanied by days of inversion conditions in complex terrain. In 2012, only fire management personnel were monitored, so project fire management personnel are a separate category from firefighting crewmembers at project fires. Table 1 summarizes the quantitative work duration data for personnel by fire type.

Table 1: Workday Duration Data by Fire Type

Fire Type and Personnel	n	Shift Duration (Std. Dev.) (Hours)	Fireline Duration (Std. Dev.) (Hours)
Prescribed Burns (crews)	83	10.5 (±2.7)	6.1 (±2.7)
Initial Attack (crews)	50[a]	12.4 (±3.6)	4.4 (±2.4)
Project Wildfires (crews)	417	13.6 (±1.5)	10.1 (±2.1)
Project Wildfires (managers)	31	14.5 (±2.2)	9.2 (±3.3)
Prescribed natural fires (crews)	83	13.6 (±2.2)	10.2 (±2.1)

Notes:

[a] There were 50 initial attack firefighters, but six personnel among three crews had either a 4- or a 2-incident day.

Figure 2 shows density plots of the overall shift duration and duration of fireline time observed for the 664 firefighting personnel participating in the study. The few short-duration events at project fires were generally due to fire crews ending an assignment and demobilizing from the fire, either to be sent home or to another fire.

In summary, the NTDP project found that the firefighters work long hours, usually shifts exceed 10 hours and were typically 12-15 hours in duration, with 6-10 hours on the fireline. Only when responding on initial attack (averaging 4.4 hours) did crews spend fewer hours on the fireline. Because firefighters work long shifts, traditional 8-hour shift-average occupational exposure limits such as the Permissible Exposure Limits (PELs) from the U.S. Dept. of Labor, Occupational Safety and Health Administration (OSHA), the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limits (RELs), and more recently-updated Threshold Limit Values (TLVs®) recommended by industrial hygienists must be adjusted downwards to account for the long shifts, and should also be adjusted downward further when in a 14-day on/2-day off extended deployment. The Short Term Exposure Limits (STELs) from many authoritative sources and the NIOSH Immediately Dangerous to Life and Health (IDLH) levels do not require such adjustment, but all may need to consider the additive effects of exposure to multiple contaminants in smoke. The exact adjustment will depend on the shift duration and deployment regime.

2.0.2 Overall Exposures by Fire Type

Figures 3-7 summarize the distribution of exposures to CO by fire type in box/whisker plots on a log scale. The maximum CO exposure over a 1-minute period is shown in Figure 3, along with a convenient metric for the exposure severity, the NIOSH IDLH of 1200 ppm. Figure 4 shows the maximum CO exposure over a 5-minute period, along with the STEL of 200 ppm enforced by some states. Figure 5 shows the maximum 8-hour CO exposure by fire type, and shows the 25 ppm TLV as a convenient overall metric, and Figure 6 shows the fireline-average CO exposure by fire type. Figure 7 shows the shift-average CO exposure, along with the National Wildfire Coordinating Group's 2012 Interim Guideline for wildland firefighting of 16 ppm.[12]

Figure 8 shows the distribution of fireline-average PM4 exposure by fire type, and Figure 9 shows the distribution of shift-average PM4 exposure by fire type.

Figure 10 shows the fireline-average respirable quartz by fire type (quartz was the only form of crystalline silica observed in any of these exposure samples), and Figure 11 shows the shift-average respirable quartz by fire type. Because the shift durations varied as noted above in Section 2.1.1, the significance of the shift-average respirable quartz exposures was checked by comparing them to a shift duration-adjusted PEL. The adjusted PEL was obtained by multiplying the respirable quartz PEL (presently 0.1 mg/m^3) by the ratio of 8 (hours) divided by the duration of each firefighter's work shift. Figure 12 shows how the shift-average respirable quartz exposures compared to the shift duration-adjusted PEL (values over 100% indicate

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[12] National Wildfire Coordinating Group. Monitoring and mitigating exposure to carbon monoxide and particulates at incident base camps. NWCG 006-2012. Boise, ID. 2012

exposures that exceed the PEL, after adjusting for the extended work shift duration). Table 2 summarizes key exposure distribution parameters by fire type for these data.

Table 2: Summary Metrics for Occupational Exposures among U.S. Wildland Firefighters (2009–2012)

Distribution Metrics	**CO 1-Min Avg. (ppm)**	**CO 5-Min Avg. (ppm)**	**CO 8-hr Avg. (ppm)**	**CO 8-hr Avg. (ppm)**	**CO Fireline Avg. (ppm)**	**CO Shift Avg. (ppm)**	**PM4 Shift Avg. (mg/m^{3})**	**Quartz Shift Avg. (mg/m^{3})**	**Quartz Shift PEL (%)**
OEL Criterion	**1200**	**200**	**50**	**35**	**25**	**16**	**0.7[c]**	**0.057**	**100**
Initial Attack (n)	60 [a]	60 [a]	50	50	50	50	18	18	18
UTL (95%/95% UCL)	337	208	29	29	41	17	2.2	0.567	176 [d]
95th percentile	153	132	15	15	23	9.5	0.69 [b]	0.153 [b]	280 [b]
95% UCL of mean	89	34	3.1	3.1	4.3	2.1	0.24 [b]	0.042 [b]	72 [b]
Arithmetic Mean	62	28	2.4	2.4	3.5	1.6	0.17 [b]	0.027 [b]	44 [b]
Geometric Mean	29	14	0.9	0.9	1.6	0.65	0.07	0.008	11
GSD (unitless)	3.5	3.9	5.6	5.6	5.1	5.1	4.1	6.0	7.2
Nondetects (%)	1.7	1.7	2.0	2.0	2.0	2.0	61	44	44
Exposures > OEL (%)	0.14	2.6	1.0	1.7	4.4	2.5	0.0 [b]	28 [b]	28 [b]
95% UCL of Exceedances (%)	0.65	5.7	3.1	4.5	9.2	6.0	15 [b]	50 [b]	50 [b]
Project Fire Crews (n)	417	417	417	417	417	417	80	80	80
UTL (95%,95% UCL)	610	341	50	50	45	32	2.3	0.303	517
95th percentile	518	287	40	40	36	26	1.7	0.132 [b]	211 [b]
95% UCL of mean	164	90	13	13	12	8.4	0.67	0.034 [b]	56 [b]
Arithmetic Mean	142	77	10	10	9.4	6.7	0.53	0.026 [b]	43 [b]
Geometric Mean	60	29	2.2	2.2	1.8	1.4	0.32	0.007	12
GSD (unitless)	3.7	4.0	5.8	5.8	6.1	5.9	2.7	6.9	7
Nondetects (%)	1.7	1.7	1.7	1.7	1.9	1.7	10	38	38
Exposures > OEL (%)	1.1	8.3	3.8	5.9	7.4	8.4	22	10 [b]	10 [b]
95% UCL of Exceedances (%)	1.7	10	5.1	7.4	9.2	10	29	17 [b]	17 [b]
Project Fire Managers (n)	31	31	31	31	31	31	31	31	31

Distribution Metrics	**CO 1-Min Avg. (ppm)**	**CO 5-Min Avg. (ppm)**	**CO 8-hr Avg. (ppm)**	**CO 8-hr Avg. (ppm)**	**CO Fireline Avg. (ppm)**	**CO Shift Avg. (ppm)**	**PM4 Shift Avg. (mg/m^3)**	**Quartz Shift Avg. (mg/m^3)**	**Quartz Shift PEL (%)**
OEL Criterion	**1200**	**200**	**50**	**35**	**25**	**16**	**0.7[c]**	**0.057**	**100**
UTL (95%/95% UCL)	830	496	42	42	53	25	1.1	0.044	100
95th percentile	164[b]	111[b]	7.1[b]	7.1[b]	7.9[b]	4.2[b]	0.35[b]	0.020[b]	40[b]
95% UCL of mean	66[b]	40[b]	2.6[b]	2.6[b]	3.6[b]	1.5[b]	0.22[b]	0.011[b]	21[b]
Arithmetic Mean	48[b]	28[b]	1.7[b]	1.7[b]	2.2[b]	1.0[b]	0.17[b]	0.009[b]	17[b]
Geometric Mean	18	8.6	0.31	0.31	0.30	0.19	0.11	0.007	12
GSD (unitless)	6.2	6.8	10	10	12	10	3.0	2.4	2.7
Nondetects (%)	6.5	6.5	6.5	6.5	9.7	6.5	33	27	27
Exposures > OEL (%)	0.00[b]	0.00[b]	0.00[b]	0.00[b]	0.00[b]	0.00[b]	3.3[b]	0.00[b]	0.00[b]
95% UCL of Exceedances (%)	9.2[b]	9.2[b]	9.2[b]	9.2[b]	9.2[b]	9.2[b]	15[b]	9.5[b]	9.5[b]
Prescribed Natural Fires (n)	83	83	83	83	83	83	16	16	16
UTL (95%/95% UCL)	801	453	91	91	64	53	2.4	0.049	94
95th percentile	523[b]	285[b]	49[b]	49[b]	35[b]	29[b]	0.88[b]	0.025[b]	45[b]
95% UCL of mean	102[b]	51[b]	8.0[b]	8.0[b]	6.5[b]	4.8[b]	0.31[b]	0.011[b]	18[b]
Arithmetic Mean	87[b]	43[b]	6.2[b]	6.2[b]	5.0[b]	3.8[b]	0.21[b]	0.008[b]	14[b]
Geometric Mean	44	20	1.4	1.4	1.1	0.9	0.11	0.006	9.3
GSD (unitless)	4.5	5.1	8.9	8.9	8.3	8.5	3.6	2.4	2.6
Nondetects (%)	3.6	3.6	3.6	3.6	4.8+	3.6	44	38	38
Exposures > OEL (%)	0.0[b]	0.0[b]	0.0[b]	1.2[b]	4.8[b]	7.2[b]	6.3[b]	0.0[b]	0.0[b]
95% UCL of Exceedances (%)	3.6[b]	3.5[b]	3.5[b]	5.6[b]	11[b]	14[b]	26[b]	17[b]	17[b]
Prescribed Burns (n)	83	83	83	83	83	83	15	15	15
UTL (95%/95% UCL)	476	314	60	60	55	36	3.8[b]	0.180	308
95th percentile	360	206	45	45	49	29	1.7[b]	0.047[b]	69[b]

Distribution Metrics	**CO 1-Min Avg. (ppm)**	**CO 5-Min Avg. (ppm)**	**CO 8-hr Avg. (ppm)**	**CO 8-hr Avg. (ppm)**	**CO Fireline Avg. (ppm)**	**CO Shift Avg. (ppm)**	**PM4 Shift Avg. (mg/m^3)**	**Quartz Shift Avg. (mg/m^3)**	**Quartz Shift PEL (%)**
OEL Criterion	**1200**	**200**	**50**	**35**	**25**	**16**	**0.7[c]**	**0.057**	**100**
95% UCL of mean	150	92	15	15	14	9.3	0.74 [b]	0.025 [b]	37 [b]
Arithmetic Mean	123	72	10	10	10.4	6.5	0.49 [b]	0.012 [b]	17 [b]
Geometric Mean	80	42	3.2	3.2	4.4	2.6	0.28	0.004	3.9
GSD (unitless)	2.5	2.9	4.6	4.6	3.7	3.9	3.0	4.8	5.7
Nondetects (%)	0	0	0	0	0	0	20	53	53
Exposures > OEL (%)	0.17	6.7	3.5	5.8	9.2	9.0	20 [b]	6.7 [b]	6.7 [b]
95% UCL of Exceedances (%)	0.62	11	6.5	9.7	14	14	44 [b]	28 [b]	28 [b]

Notes:

[a] 60 individual fires (Peak/STEL metrics) among 50 firefighters

[b] Nonparametric (i.e., Kaplan-Meier or other nonparametric) estimate because of variability and/or proportion of left-censored data.

[c] This is a shift-duration-ratio reduction of a working OEL of 1 mg/m^3, until a risk assessment identifies a more suitable standard.

[d] The highest detected exposure, because the highest exposure was nondetected and the UTL is unstable with this small data set.

[+] Percentage increase because one firefighter’s CO exposure occurred before deployment on the fireline

The data show great variability, with GSDs well above 4 in many cases. The cause for this was examined through the MLMs for each major response variable, as discussed in Sections 2.1 through 2.4 below.

In summary, because the shifts exceed the traditional workplace in both duration and relief time (for 14-day on/2-day off schedules), exposure limits must be adjusted downward. A range of recommended exposure limits (and for PELs, the minimum acceptable exposure limits) are presented and by any measure it is not uncommon for firefighters to exceed adjusted occupational exposure limits. As firefighters become managers in their careers, their exposures are seldom over relevant occupational exposure limits. However, while employed as firefighters on typical crews, they are likely to exceed recommended CO exposure limits, PELs for respirable crystalline silica, and recommended occupational exposure limits for PM4.

2.1 5-MINUTE MAXIMUM CO EXPOSURE

The objective of this analysis was to assess whether the 5-minute maximum-average CO exposure was a function of categorical and continuous fixed variables available in the data collected by NTDP staff from 2009-2012. The log of 5-minute maximum average CO exposure was used as the response variable (y) because the distribution approximated a lognormal distribution. A multilevel mixed-effects linear model was developed to estimate observed exposures. Of 677 observations of 5-minute maximum-average CO exposure (including the 2012 fire management personnel), restricting the analysis to just the 2009-2011 firefighters (on the assumption that fire managers had fundamentally different exposures) left 643 observations among firefighters, of which a few were different 5-minute maxima from among two to several incidents in a day for a given pair of FFs at initial attack events in Texas. The random factor "*daycrew*" was a grouping factor which averaged zero, but accounted for each firefighter on a crew experiencing a unique combination of environmental and individual crew characteristics. The intraclass correlation coefficient (ICC) for 5-minute maximum CO exposure by *daycrew* was calculated to be 0.64. So, 64% of the variation in fireline-average CO exposures among firefighters was due to which crew and day they happened to be observed on, a "random" factor that was not useful as a future predictor of exposure. Exposures were more alike within the grouping of up to nine firefighters per crew-day than they were by alternatively grouping among different crews (ICC=0.43), or at different fires (ICC=0.31), or at crew within fire (ICC=0.54). For this reason, the multilevel model was selected, where fixed effects of explanatory variables were tested after grouping by the *daycrew* factor.

For 5-minute maximum CO exposure, we had more flexibility in testing predictive factors than was possible with fireline-average CO exposure. Unfortunately, there were many observations that had no data for potentially useful factors:

- Fuel model was not recorded in 6% of the records;
- Wind speed and canopy coverage were missing in over 9% of the records;
- Up/downwind position was missing in 14% of the data;
- Up/downhill status was missing in 26% of the records; and
- The inversion presence, years of experience of the firefighter and of the supervisor were missing in over 40% of the records.

Some factors were not observed at all in 2009, so after dropping records with missing observations for the key factors kept in the final model, the simplest model that explained most of the remaining exposure variability included 585 observations of 5-minute maximum CO exposure, clustered among 207 unique crew-days (factor "daycrew"). It was finalized using the step function in the R package *LmerTest* and made use of the following categorical and continuous fixed-effect factors:

- Crew type—[Dozer(I/II/III), Engine(II,III/IV), Engine(VI), I/I(IHC), II (IA), or II/Fuels].
- Activity observed during or nearest to the maximum CO exposure event for the firefighter—(Ancillary, Dozer/tractor plow operator or dozer operations boss "DozerOps", direct handline construction and sawyer "Handline/Saw(Dir)", and indirect Handline/Saw(Ind)], Holding, Lighter and lighting boss "LightingOps", Mop up, and engine or portable pump operator "Pump Op"). The "ancillary" work activity included all activities not involved in fire management efforts, such as: driving or hiking to a work zone, attending a pre-task briefing, standing by for orders, taking lunch or other breaks, and so forth.
- Wind speed observation during or nearest the maximum CO exposure event for the firefighter (*Windspeed.5*), centered as a hedge against collinearity by subtracting the grand mean average of the wind speed observations for the data set (which was 2.5 mph). Negative values indicate less than average wind speed (in mph), positive values indicate more than average wind speed (in mph); and
- The interaction between the centered wind speed and the work activity during that time.

Fire type, and simplified categories of fuel model (light, medium, and heavy fuels), fire behavior, USFS Region, and up/downwind position were all not significant and dropped from the model. The final multilevel mixed model that resulted (*co.stelmodel.6*) was a two-level model, with each firefighter being nested within a given crew for each day (daycrew). The model can be summarized as:

$$log5Min.CO = CrewType + 5.Min.Activity + Ctr.Windspeed.5 + 5.Min.Activity{:}Ctr.Windspeed.5$$

Where:

Log5.Min.CO = the log of the maximum 5-minute-average carbon monoxide concentration (adjusted for the method detection limit),

CrewType = The firefighter crew category,

5.Min.Activity = The work activity represented during or prior to the 5-minute maximum CO exposure,

Ctr.Windspeed.5 = The grand mean centered wind speed observation during or prior to the maximum CO exposure; and

5.Min.Activity:Ctr.Windspeed.5 = The interaction between the work activity and the centered wind speed observation.

LmerTest reported a Chi-square value of 145 in the model for the random effect *daycrew*, (probability <1e-07). After using LME4 and maximum likelihood parameter estimates to compare the addition of the fixed effects to the null model, ANOVA indicated a highly-significant Chi-square value of 88 (Probability <1.4e-10). Population fixed effect estimates for the model parameters are listed in Table 3; the degrees of freedom, t-statistics and probabilities were calculated in package lmerTest using the Satterthwaite method of estimation.

Table 3: Least-squares means estimates for log maximum 5-minute average carbon monoxide exposure among US wildland firefighters, 2009-2011

Parameter:Category	Estimate	Std. Error	df	t value	Pr(>|t|)	Sig.
Crew.Type Dozer(I/II/III)	2.461	0.368	401	6.68	<2e-16	***
Crew.Type Engine(II/III/IV)	2.447	0.250	212	9.80	<2e-16	***
Crew.Type Engine(VI)	3.254	0.253	228	12.88	<2e-16	***
Crew.Type I/I(IHC)	3.409	0.127	327	26.81	<2e-16	***
Crew.Type II (IA)	3.824	0.286	197	13.37	<2e-16	***
Crew.Type II/Fuels	3.732	0.206	227	18.13	<2e-16	***
5.Min.Activity Ancillary	2.651	0.143	455	18.59	<2e-16	***
5.Min.Activity DozerOps	3.815	0.385	561	9.91	<2e-16	***
5.Min.Activity Handline/Saw(Dir)	3.530	0.157	452	22.43	<2e-16	***
5.Min.Activity Handline/Saw(Ind)	3.480	0.203	406	17.17	<2e-16	***
5.Min.Activity Holding	3.299	0.152	427	21.71	<2e-16	***

5.Min.Activity LightingOps	3.059	0.191	517	16.03	<2e-16	***
5.Min.Activity Mop up	3.182	0.137	398	23.23	<2e-16	***
5.Min.Activity Pump Op	2.487	0.491	551	5.07	<2e-16	***

Notes: Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Model plots by explanatory factors are discussed below. A general statement for some of these figures is that a better fit might be obtained by fitting a curvilinear model, especially at lower concentrations of CO. Exploring this and applying a bootstrap analysis to assess the stability of the factors with different random subsets of the data would be worthwhile, especially after another detailed pass through the data to reconstruct missing observations for all factors. Because a multilevel model adjusts for categorical fixed and random factors, a typical line plot that we might obtain when modeling versus a single predictor is impossible. To show the overall fit to the data after adjusting for all factors, we are presenting the adjusted data and the observed data against the observed data by each fixed effect in the model. In these plots, the observed data show a perfect linear 1:1 fit. The model results are offset from the perfect fit by the specific additive model of the means for each level of each categorical factor (including factors that were in the final model but not shown in each figure). This can be readily seen by jumping ahead to the upper left panel of Figure 22, where there were just four observations of fireline-average CO exposure during wind conditions that were “both” upwind and downwind from smoke sources. All four firefighters were also on a *Type II/Fuel*s crew, performing “*holding*” during most of their fireline time (which was 14.9% less than the 49% average for the main task), and at the same fire, day and crew (thus in the same “*daycrew*” and influenced by the random effect for that crew and day). Because they all had the same predictive factors, the model calculated the same fitted log fireline-average CO exposure value of 2.45, as indicated by the blue symbols, which deviate from the observed fireline-average by their individual vertical distances from a line passing through the red symbols. In contrast, the estimates for the panel to the right in Figure 22 (“Calm”) were for 17 firefighters distributed among three different crew types, and the firefighters undertook six different main activities that made up five different percentages of the total fireline time, and five different “*daycrew*” values.

Figure 13 shows the model-adjusted fitted values (blue scattered symbols) versus the observed values (red linear symbols) for the linear MLM for (log) 5-minute maximum average CO exposure by crew type. A linear mixed model is a reasonably good fit across all levels of this factor.

Figure 14 shows the model-adjusted fitted values (blue scattered symbols) versus the observed values (red linear symbols) for the linear MLM for (log) 5-minute maximum average CO exposure by work activity. The fitted values are reasonably consistent with the 1:1 observed values across each work activity during the 5-minute maximum exposure period. Ancillary tasks could involve many non-firefighting activities such as hiking to or along fire lines, but were frequently situations where firefighters were taking a break, being briefed, or otherwise waiting. Sometimes these tasks were in smoke or by idling vehicles, at others they could be in relatively pristine conditions. The highest observed CO exposure during “ancillary” tasks (240 ppm) occurred while the firefighter was traveling in a vehicle. If the observation of task truly aligned with his 5-minute exposure, it might have been due to either traveling through a smoky section or while vehicle exhaust affected the firefighter. Model adjustments for the explanatory factors retained in the final model resulted in a fitted 5-minute CO exposure estimate of 48 ppm for this firefighter. Clearly further refinements could be made to explain and possibly exclude outliers, which might reduce differences between the actual observed and fitted 5-minute maximum CO exposures.

Figure 15 shows the fitted values (in blue) for (log) 5-minute maximum average CO exposure versus the difference in ambient wind speed (from the average of 2.5 mph) by work activity. On the x-axis, points to the right of zero occurred when the wind was above average, ranging up to over 10.5 mph (2.5 + 8). Points to the left were in calmer conditions, down to zero mph. There appears to be a weak trend associating higher adjusted CO exposure with higher wind speeds when firefighters are holding firelines, and possibly during lighting and pump operation tasks. The former two would probably not be surprising conclusions to experienced firefighters. For ancillary tasks, the highest adjusted CO exposures might be associated with calmer conditions, such as during early morning briefings near operating engines and in morning inversion situations.

Figure 16 shows the fitted values (blue scattered symbols) for (log) 5-minute maximum average CO exposure along with the 1:1 observed (log) 5-minute maximum average CO exposure (red linear symbols) by fire type, which was dropped from the model as a nonsignificant factor. There doesn’t appear to be a major misfit by any particular fire type. All tend to show a somewhat higher adjusted CO concentration than was observed at lower concentrations.

Figure 17 shows the fitted values (blue scattered symbols) for (log) 5-minute maximum average CO exposure along with the 1:1 observed (log) 5-minute maximum average CO exposure (red linear symbols) by USFS Region. Although the factor ‘Region’ was dropped from the final model because it was nonsignificant, the model fit to the data was reasonably consistent across all regions of the country.

Figure 18 shows the contrasts in least-squares means for the levels of fixed-effect factors in the 5-minute CO exposure model. These are the differences in the fixed effect means, after adjusting for the effects of other variables. From these plots we can see the 95% confidence intervals on the differences in the individual means for each level of each categorical variable (the dark line with end-hatches), and the differences in those means (the thick gray or colored bars). Red bars represent factor levels that are most significantly different (probability p<0.001), orange are very significantly different (p < 0.01), and yellow are significantly different (p<0.05). The left plot (titled "Crew.Type") indicates that for this factor:

- The maximum 5-minute average CO exposure was significantly higher among Type I/I(IHC) crews, Type II(IA) and Type II(Fuels) crews than among Dozer(I/II/III) personnel, and the difference was even more significant versus Engine (II/III/IV) crews.
- Maximum 5-minute average CO exposures among Type II(IA) and Type II(Fuels) crews were not significantly lower than Type I and I(IHC) crews.
- Maximum 5-minute average CO exposures among Engine(VI) crews were significantly higher than Engine(II,III/IV) personnel.
- Maximum 5-minute average CO exposures among dozer/tractor-plow operators and dozer bosses (Dozer(I/II/III) were no different than the Engine (II/III/IV) crews. Although the maximum 5-minute average CO exposures among the Engine(VI) exposures were higher than the Dozer(I/II/III) crews, the difference was not significant.

The right plot (titled ""X5.Min.Act2") shows that for the tasks associated with the maximum 5-minute average CO exposure in the shift:

- The maximum 5-minute average CO exposures were significantly lower during ancillary tasks than all but the pump operator task;
- The maximum 5-minute average CO exposures among dozer operators were not significantly higher than all but the pump operator task;
- The maximum 5-minute average CO exposures among Handline/Sawyer(Direct) tasks were significantly higher than during lighting, mop up and pump operation tasks, but were not significantly higher than Handline/Sawyer(Indirect) or Holding.

In summary, the factors determining the personal daily maximum short-term exposures (5-minute average) for the firefighters were tested in a multilevel mixed-effects linear model, where the day and crew provided a random grouping factor. Of the available predictive factors for the maximum 5-minute exposure, only the crew type, the work activity, and the wind speed and its interaction with work activity were significant predictors. Other factors may matter but the data were not complete enough to test this. As for crew type, the highest average 5-minute CO exposures were for Type II(Fuels) and Type II(IA) crews (42 and 46 ppm). They were significantly higher than most wildland Engine(II/III/IV) crews (12 ppm), but not significantly higher than Engine(VI) crews (26 ppm). The Type I/I(IHC) crews averaged 30 ppm, but weren't significantly lower than the Type II crews. The 5-

minute maximum CO exposures among Type I and Type II crews were both significantly higher than dozer crews (12 ppm). The 5-minute maximum CO exposures among dozer and engine crews were not significantly different. Based on these data, Type II and Type I crews, and Engine(VI) crews should be the focus of peak exposure reduction.

Of the work activities, the highest average 5-minute exposures were experienced during dozer operations (45 ppm—during initial attack) but these were not significantly higher than among those performing handline/sawyer activities (32-34 ppm, for indirect and direct line construction respectively). The highest average 5-minute CO exposures during dozer operations were significantly higher than among pump operations (12 ppm), but no other fireline activities except ancillary tasks like hiking, briefings, breaks and during standby). Handline/sawyer (direct line construction) had higher 5-minute maximum CO exposures than lighting (21 ppm), mop up (24 ppm), and pump operations, but they were not significantly higher than during holding operations (27 ppm). Windspeed had a very significantly positive effect on exposures among dozer operators, and a slightly positive effect among personnel holding and lighting. The factor analysis data indicate that peak exposure interventions might be most effective among initial attack dozer operations, handline/sawyer activities, and while holding firelines.

2.2 FIRELINE-AVERAGE CO EXPOSURE

Factors that might control exposure were noted by observers at the start of time on the fireline, and roughly hourly through the remainder of the day—each interval comprising a period of time in the day defined by a start and end time. Because of changes in activity, location or simply observational opportunities, the number of unique observation periods varied between one and 18 periods within a given day, depending on the firefighter. Each observation period was defined by entries for potential explanatory fixed variables. An array of the observations of work activity, fuel model, wind position relative to the fire, windspeed (mph), slope position relative to the fire, slope (%), and many other variables was created with a start and stop time, and net duration of each period. With this array, the percentage of fireline time represented by a specific combination of potential explanatory variables could be summed across each firefighter’s shift, representing a weighting factor that defined how much of the fireline time the combination represented for each firefighter.

Consider an example day where a firefighter was lighting upwind of the fire for 4 hours, holding fireline upwind of the fire for 2 hours, and holding fireline downwind of the fire for 2 hours. If we only considered his work activity, his 8 hours of fireline time were: 50% lighting and 50% holding. If activity and wind position were of interest, re-aggregating the time across the additional factor resulted in 50% lighting upwind, 25% holding upwind, and 25% holding downwind—a different set of weightings. As the observation results for additional potentially explanatory factors were added, the percentage of time for any individual combination would decrease, leading to the tradeoff between more predictive power for fewer variables (because they represent more of the fireline time) and less predictive power spread among more variables (though they might be important, they may individually represent less of the fireline time). There is also the typical tradeoff between degrees of freedom and number of factors or levels of a categorical factor in the analysis of variance. We combined levels of a factor when there were few observations within a level, such as for fuel model.

Work activities, field conditions (wind direction and speed, firefighter position up or downwind of the fire, temperature, relative humidity, fuel model that was burning, slope, position on slope relative to fire), and fire conditions (fire activity, flame length, backing or heading, etc.) were all measured, but many variables were not observed during every period of the time on the fireline for every firefighter. This created a significant data completeness problem that prevented a fuller examination of potential relationships among these data. The missing observations reduce available power because any firefighter with a missing factor observation had to be dropped from the data subset used for modeling that combination of factors. For this reason, our analysis was unable to make use of all the potential factors that could have been assessed with a more complete data set.

For the fireline-average CO exposures, the best null model (clustering by the factor *daycrew*) had an intraclass correlation coefficient (ICC) of 0.67. So a substantial amount of the variation in fireline-average CO exposures among firefighters was due to which crew and day they happened to be observed on, a “random” factor that was not useful as a future predictor of exposure. For CO, the simplest model that explained most of the remaining exposure variability while including all 621 observations (firefighters’ fireline-average CO exposure), was clustered among 208 unique crew-days (factor “daycrew”). It made use of the following categorical and continuous fixed-effect factors:

- Crew type—[Dozer(I/II/III), Engine(II), Engine(III/IV), Engine(VI), I/I(IHC), II (IA), or II/Fuels];
- Position in the wind relative to the fire—(Both, Calm, Downwind, or Upwind);
- Majority activity during the fireline time—(Ancillary, Dozer or tractor plow operator or dozer operations boss “DozerOps”, direct handline construction and sawyer “Handline/Saw(Dir)”, and indirect Handline/Saw(Ind), Holding, Lighter and lighting boss “LightingOps”, Mop up, and engine or portable pump operator “Pump Op”). The “ancillary” work activity included all activities not involved in fire management efforts, such as: driving or hiking to a work zone, attending a pre-task briefing, standing by for orders, taking lunch or other breaks, and so forth;
- Percentage of fireline time that the majority combination of variables represented, centered by subtracting the grand mean percentage of fireline time represented by the majority activity, fuel model and wind condition (which was 49%). Negative values indicate less than average time in the activity, positive values indicate more than average time; and

- The interaction between the majority factor time and the work activity during that time. This is intuitive because if an activity was an important determinant of exposure, the more time that activity represented, the stronger effect it would exert.

Fire type was nearly significant but failed by F-test. Simplified categories of fuel model (light, medium, and heavy fuels) during the majority activity were considered but did not improve the model. Flame height, fire behavior, canopy percentage, slope and uphill/downhill were all not improvements to the model. Region (USFS Region) significantly improved the model but none of the individual region levels had a significant coefficient, so this categorical factor was dropped. Attempting to use the second-most and third-most prevalent activity/factor combinations within each firefighter's fireline time was discontinued because of increasing loss of data due to missing observations.

The final multilevel mixed model that resulted (*co.model1.8c2*) was a two-level model, with each firefighter being nested within a given crew for each day (daycrew)—a random nuisance factor which averages zero but accounts for about 42% of the variation in fireline-average CO, while the fixed effects explained 34% (via partial r^2 calculations—Finch et al, 2014. Pp. 47-48). The model can be summarized as:

$$\begin{aligned} &logFireline.CO \\ &\qquad = CrewType + Activity2.1.1 + Ctr.PctFireline1 + WindPosition1 \\ &\qquad + Activity2.1.1{:}\,Ctr.PctFireline1 \end{aligned}$$

Where:

logFireline.CO = the log of the fireline-average carbon monoxide concentration (adjusted for the method detection limit),

CrewType = The firefighter crew category,

Activity2.1.1 = The most-performed activity represented in the time on the fireline (for a given state of all the other final factors in the model),

Ctr.PctFireline1 = The grand mean centered percentage of fireline time represented by the most-performed activity,

WindPosition1 = The wind field position of the firefighter relative to the fire; and

Activity2.1.1:Ctr.PctFireline1 = The interaction between the work activity and the percentage of fireline time that it represents.

LmerTest reported a Chi-square value of 185 for the random effect *daycrew*, (probability <1e-07). Population fixed effect estimates for the model parameters are listed in Table 4; the degrees of freedom, t-statistics and probabilities were calculated in package "lmerTest" using the Satterthwaite method of estimation.

Table 4: Least-squares means estimates for log Fireline-average carbon monoxide exposure among US wildland firefighters, 2009-2011

Parameter:Category	Estimate	Std. Error	df	t value	Pr(>|t|)	Sig.
Crew.Type Dozer(I/II/III)	0.0327	0.5885	280	0.06	0.956	
Crew.Type Engine(II)	0.4052	1.0412	188	0.39	0.698	
Crew.Type Engine(III/IV)	-0.1053	0.5125	191	-0.21	0.837	
Crew.Type Engine(VI)	0.9944	0.4973	199	2.00	0.047	*
Crew.Type I/I(IHC)	0.7819	0.4069	195	1.92	0.056	.
Crew.Type II (IA)	1.3193	0.5426	194	2.43	0.016	*
Crew.Type II/Fuels	1.4721	0.4353	191	3.38	0.001	***
Activity2.1.1 Ancillary	-0.0988	0.4288	192	-0.23	0.818	
Activity2.1.1 DozerOps	0.9641	0.6269	375	1.54	0.125	
Activity2.1.1 Handline/Saw(Dir)	1.6207	0.5315	241	3.05	0.003	**
Activity2.1.1 Handline/Saw(Ind)	1.0268	0.5385	212	1.91	0.058	.
Activity2.1.1 Holding	1.2203	0.4359	189	2.80	0.006	**
Activity2.1.1 LightingOps	0.5876	0.5098	250	1.15	0.250	
Activity2.1.1 Mop up	0.3407	0.4421	191	0.77	0.442	
Activity2.1.1 Pump Op	-0.0611	0.7552	559	-0.08	0.936	
Up.Downwind.1 Both	0.9265	1.3652	173	0.68	0.498	
Up.Downwind.1 Calm	0.6078	0.6629	196	0.92	0.360	
Up.Downwind.1 Downwind	0.9873	0.2216	255	4.46	<2e-16	***
Up.Downwind.1 Upwind	0.2786	0.2147	261	1.30	0.196	

Notes: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Model plots by explanatory factors are discussed below. A general statement for some of these figures is that a slightly better fit might result by fitting a curvilinear model, especially at lower concentrations of CO. Figure 19 shows the fit and observed values of the linear MLM for (log) fireline-average CO exposure by crew type. The mixed model is a reasonably good fit across all levels of this factor, which had significant coefficients for Engine(VI), Type II(IA), and Type II(Fuels).   Crew type of Type I/I(IHC) just missed significance.

Figure 20 shows the fireline-average CO model fit by fire type (which was the last factor eliminated from the model by stepwise reduction in lmerTest, with an F value probability of 0.18). Initial attack had a fairly broad spread in observed fireline-average CO exposures, whereas prescribed burning was a bit more consistent. We might expect this because the initial attack efforts were usually around very small incidents, and so if the initial attack could successfully approach from the tail and flanks, their time in substantial smoke downwind of the fire might be very limited. On other occasions, the geography or the wind consistency might not allow the crew to successfully avoid the smoke. Most of the initial attack crews were operating with dozers/tractor plow equipment or wildland engines.

Figure 21 shows the fireline-average CO model fit by majority task on the fireline for each firefighter. Ancillary tasks could involve many non-firefighting activities where firefighters are waiting, sometimes in smoke or by idling vehicles, at others they could be in relatively pristine conditions. Handline/sawyer(Direct) and Holding were significantly higher mean exposures than Ancillary tasks.

Figure 22 shows the fireline-average CO model fit by position up- or downwind of the nearest source of smoke. Mopping-up is an example of a task where a firefighter could be both up- and downwind of smoke sources.

Figure 23 shows the fireline-average CO model fit (adjusted for all factors) versus the grand mean centered percentage of time in the main task. The average firefighter spent 49% of their fireline time in the main task, and the centering subtracted this mean from each observation. So a value of -0.4 means that the firefighter spent just 9% of their time doing this main task, a value of 0 means they spent 49% of their time doing the task, and a value of 0.4 means they spent 89% of their time doing this task. It is apparent that the more time spent performing ancillary activities, the lower the CO exposure on the fireline. Pump operator shows a similar trend though there were few points. A significant positive trend exists for CO exposure versus the time spent in direct handline/sawyer operations. Similarly, weaker but still significant positive trends in CO exposure versus the time spent in the main task were found for indirect handline/sawyer operations, holding fireline, and lighting operations. No trend was observed for amount of time where mop up was the main task.

Figure 24 shows the observed and model-fitted fireline-average CO exposure by USFS Region. Although the factor ‘Region’ was dropped from the final model because it was nonsignificant, the model fit to the data was reasonably consistent across all regions of the country.

Figure 25 shows the contrasts in least-squares means for the levels of fixed-effect factors in the model. These are the differences in the fixed effect means, after adjusting for the effects of other variables. From these plots we can see the 95% confidence intervals on the differences in the individual means for each level of each categorical variable (the dark line with end-hatches), and the differences in those means (the thick gray or colored bars). Red bars represent factor levels that are most significantly different (probability $p<0.001$), orange are very significantly different ($p < 0.01$), and yellow are significantly different ($p<0.05$). The leftmost plot titled “Activity2.1.1” shows that for the majority tasks (which averaged 49% of fireline time):

- As we might expect, the ancillary tasks had significantly lower fireline-average CO exposure than almost every other task;
- Handline/Sawyer(Direct) tasks had significantly higher fireline-average CO exposure than lighting, mop up, and pump operator;
- Holding line was associated with significantly higher fireline-average CO exposure than lighting and mop up.

The center plot (titled “Crew.Type”) shows that for this factor:

- Fireline-average CO exposure was significantly higher among Type II(Fuels) and Type II(IA) crews than among Engine (III/IV) personnel, and Type II(Fuels) crews had higher fireline-average CO exposures than Type I and I(IHC) crews.
- Engine(VI) fireline-average CO exposures were significantly higher than Engine(III/IV) personnel, as were the exposures of Type I/I(IHC) crews.
- Dozer and tractor-plow operators and dozer bosses also had lower fireline-average CO exposures than the Type II(IA) and II(Fuels) crews.

Finally, the right plot of Figure 25 (titled “Up.Downwind.1”) confirms a truism from the average campfire applies to wildland fire operations: persons downwind of the fire are significantly more exposed to smoke than persons upwind.

Similar exposure groups (SEGs) can be established from these data and figures. For example, estimated fireline-average exposures could be specifically examined among Type I/I(IHC), Type II(Fuels) or Type II(IA) crews performing fireline holding or Handline/Sawyer(Direct) tasks in downwind situations. A long-term CO surveillance project might be appropriately focused on tracking and assessing the effectiveness of mitigation strategies for fireline-average CO exposure among these crews doing these tasks in these conditions, as the model indicates that based on these data, they will have the highest fireline-average CO exposures. By grouping future data by these crew, task and wind position categories, the inherent variability of the results may be reduced, thereby improving the ability to detect a real reduction of exposure from a given mitigation strategy.

As plots show, the model fit could certainly be improved with nonlinear modeling, but that exercise did not seem warranted at this time given the observational nature of the data and the many missing observations. Careful backfilling of missing data could also probably be done if those who gathered the data could review the data gaps and supply recollections or inferred conditions where the notes were missing data.

In summary, for fireline-average exposures, replication within a crew and day was only available for CO; this exposure metric also had many more observations than the fireline-average PM4 and quartz data. A multilevel mixed-effects model using day and crew as a grouping factor was developed. Factors such as fuel model, wind speed, fire behavior and other variables were considered but dropped due to missing observations. The final model which made use of the most observations found that the crew type, the activity representing most of the fireline time and the amount of time it represented, and the position up or downwind of the fire were significant determinants of CO exposure. For fireline-average CO exposure, being mainly downwind of the fire obviously leads to significantly higher exposures vs. upwind. Among the crew types, the Type II(Fuels) and Type II(IA) crews had the highest fireline-average CO exposures, significantly higher than Engine(III/IV) and Dozer(I/II/III) crews, and Type II(Fuels) was even significantly higher than Type I/I(IHC). Fireline-average CO exposures among Type II(IA) crews were also higher than I/I(IHC) but not significantly so.

Among the activities that made up most of the time on the fireline, those performing Handline/sawyer(direct) tasks had significantly higher CO exposures than those doing mainly lighting tasks (lighting and lighting boss), pump operations and mop up. Exposures among those mainly holding fireline were significantly higher than those doing the lighting tasks, and those doing mop up. As might be expected, when ancillary tasks predominated (hiking, standby/staging, briefing), exposures were low. The fireline-average CO data indicate that management interventions will be most effective if focused on Type II and Type I/I(IHC) crews, especially when they are performing direct handline/sawyer assignments and holding fireline, and unavoidably downwind of the fire.

2.3 FIRELINE-AVERAGE RESPIRABLE PARTICULATE MATTER EXPOSURE

There were 128 observations of PM4 exposure among firefighters in 2010-2011 (data were not collected for PM4 in 2009). Unlike the data for CO, there was generally only one PM4 sample taken per crew. This lack of replication meant we could not apply the same strategy of using "*daycrew*" as a clustering factor. The factor "*Crew.Name*" was tried and resulted in an ICC of 0.42. The best hierarchy was obtained by using *Crew.Name* within *Fire.Name*, which produced an ICC of 0.60. This formed the null model for comparing fixed effects.

For PM4, the simplest model that included all 128 observations of firefighters' fireline-average PM4 exposure was clustered among 50 fire names, and 104 crew names within them (several crews were sampled on more than one day within a given project wildfire or PNF). It made use of the following categorical and continuous fixed-effect factors:

- Crew type—[Dozer(I/II/III), Engine(II), Engine(III/IV), Engine(VI), I/I(IHC), II (IA), or II/Fuels];
- Position in the wind relative to the fire—(Calm, Downwind, or Upwind);
- Majority activity during the fireline time—(Ancillary, Dozer or tractor plow operator or dozer operations boss "DozerOps", direct handline construction and sawyer "Handline/Saw(Dir)", and indirect Handline/Saw(Ind), Holding, Lighter and lighting boss "LightingOps", and Mop up).

Fire type and percentage of time that the main activity occurred were not significant in the model for PM4 exposure and were dropped. There were not enough observations of other factors to include them in the model.

The final multilevel mixed model that resulted (*pm4.model1.8a*) was a three-level model, with each firefighter being nested within a given crew for a given fire. The model can be summarized as:

$$logFireline.PM4 = CrewType + Activity2.1.1 + WindPosition1$$

Where:

logFireline.PM4 = the log of the fireline-average PM4 concentration (adjusted for the method detection limit),

CrewType = The firefighter crew category, *Activity2.1.1* = The most-performed activity represented in the time on the fireline (for a given state of all the other final factors in the model); and

WindPosition1 = The wind field position of the firefighter relative to the fire.

LmerTest reported a Chi-square value of 6.5 for the random effects *Fire.Name2/Crew.Name*, (probability <0.01). Population fixed effect estimates for the model parameters are listed in Table 5; the degrees of freedom, t-statistics and probabilities were calculated in package "lmerTest" using the Satterthwaite method of estimation.

Table 5: Least-squares means estimates for log Fireline-average respirable particulate matter exposure among US wildland firefighters, 2010-2011

Parameter:Category	Estimate	Std. Error	df	t value	Pr(>|t|)	Sig.
Activity2.1.1 Ancillary	-1.144	0.214	100	-5.35	<2e-16	***
Activity2.1.1 DozerOps	-0.969	0.415	77	-2.33	0.022	*
Activity2.1.1 Handline/Saw(Dir)	-0.994	0.421	111	-2.36	0.020	*
Activity2.1.1 Handline/Saw(Ind)	-1.425	0.414	84	-3.44	0.001	***
Activity2.1.1 Holding	-0.786	0.262	110	-3.01	0.003	**
Activity2.1.1 LightingOps	-1.073	0.352	108	-3.05	0.003	**
Activity2.1.1 Mop up	-0.428	0.230	111	-1.86	0.028	.
Up.Downwind.1 Calm	-1.025	0.406	95	-2.52	0.013	*
Up.Downwind.1 Downwind	-0.730	0.180	91	-4.07	1e-04	***
Up.Downwind.1 Upwind	-1.167	0.170	94	-6.87	<2e-16	***
Crew.Type Dozer(I/II/III)	-0.724	0.383	92	-1.89	0.062	.
Crew.Type Engine(II)	-0.988	0.743	49	-1.33	0.190	
Crew.Type Engine(III/IV)	-1.583	0.310	107	-5.10	<2e-16	***
Crew.Type Engine(VI)	-1.029	0.283	58	-3.64	6e-04	***
Crew.Type I/I(IHC)	-0.818	0.192	69	-4.25	1e-04	***
Crew.Type II (IA)	-1.110	0.366	88	-3.03	0.003	**
Crew.Type II/Fuels	-0.567	0.272	112	-2.09	0.039	*

Notes: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Model plots by explanatory factors are discussed below. A general statement for some of these figures is that a slightly better fit might result by fitting a curvilinear model, especially at lower concentrations of PM4. Figure 26 shows the fit and observed values of the linear MLM for (log) fireline-average PM4 exposure by crew type, a factor that was kept in the model. The mixed model is a reasonably good fit across most levels of this factor, which had significant coefficients for all but Engine(II). The model tends to over-predict PM4 exposure for low exposures, and under-predict at high exposures, especially for dozer operations, Type I/I(IHC) and Type II/Fuels and Type II(IA) crews. Dozer operations tend to have extremely dusty operations, potentially causing high operator exposures to respirable dust. No attempt was made to separately analyze exposures in enclosed-cab dozers, but their dust exposures should be lower than open-cab models if they are well-maintained and operated with the windows shut.

Figure 27 shows the fireline-average PM4 model fit by fire type (which was not retained in the model). The model underpredicts initial attack PM4 exposures. Of these initial attack personnel, 67% were also dozer operators or dozer bosses. This group would thus dominate the effect of the initial attack factor had it been included in the model. The model generally over-predicts low PM4 exposures and under-predicts high exposures for all fire types.

Figure 28 shows the fireline-average PM4 model fit by majority task on the fireline for each firefighter, a factor that was retained in the model. For PM4 samples, the main task averaged 45% of the fireline time. The model trends versus levels of main task are similar to other factors (over-prediction of low concentrations and under-prediction of high concentrations), but appear less pronounced versus most task types.

Figure 29 shows the fireline-average PM4 model fit by position up- or downwind of the nearest source of smoke. The model fit is generally similar to the observed results for most of the range for each category of wind position.

Figure 30 shows the fireline-average PM4 model fit versus the grand mean centered percentage of time in the main task. This factor was dropped from the model during simplification. The average firefighter in the group with PM4 data spent 45% of their fireline time in the main task, and the centering subtracted this mean from each observation. So a value of -0.4 means that the firefighter spent just 5% of their fireline time doing this main task, a value of 0 means they spent 45% of their time doing the task, and a value of 0.4 means they spent 89% of their time doing this task. As was seen for CO exposure, the more time spent performing ancillary activities, the lower the PM4 exposure on the fireline.

Figure 31 shows the observed and model-fitted fireline-average PM4 exposure by USFS Region. The factor 'Region' was dropped from the final model because it was nonsignificant. The model fit to the data was reasonably consistent across all regions of the country.

Figure 32 shows the contrasts among least-squares means for the levels of fixed-effect factors in the model. These are the differences in the means by category, after adjusting for the effects of other variables. From these plots we can see the 95% confidence intervals on the differences in the individual means for each level of each categorical variable (the dark line with end-hatches), and the differences in those means (the thick gray or colored bars). Red bars represent factor levels that are most significantly different (probability p<0.001), orange are very significantly different (p < 0.01), and yellow are significantly different (p<0.05). The leftmost plot titled "Activity2.1.1" shows that for the majority tasks (which averaged 45% of fireline time for firefighters with PM4 results):

- Ancillary tasks had lower fireline-average PM4 exposure than almost every other task (there were only four samples of Handline/Sawyer(Indirect), so we cannot rule out an unrepresentative sample), but only the PM4 exposure during Mop-up was significantly higher than the ancillary tasks;
- Those mainly performing the Mop-up task also had a significantly higher fireline-average PM4 exposure than the Handline/Sawyer(Ind) group, based on a relatively small number of firefighters for the latter;
- As might be expected, holding line was associated with higher fireline-average PM4 exposure than lighting, but not significantly so.

The center plot (titled "Crew.Type") shows that for this factor:

- Fireline-average PM4 exposure was significantly higher among Type II(Fuels) and Type II(IA) crews than among Engine (III/IV) personnel, and Type II(Fuels) crews had higher fireline-average PM4 exposures than Type I and I(IHC) crews.
- Engine crews generally had lower fireline-average PM4 exposures than other crew types; the apparently higher exposure for the Engine(II) crews than the Type II(Fuels) crews was likely an unrepresentative result due to there being only two samples for PM4 in the Engine(II), one of which spent their main task on the fireline performing mop-up. The Engine(III/IV) crews had significantly lower fireline-average PM4 exposures than the Type I/I(IHC) and Type II(Fuels) crews. 67% of the Type II(IA) were performing "Holding" activities, which are often a higher-exposure potential situation and would tend to cause their exposures to be higher than Type I/I(IHC) crews, who's main tasks were usually something else, as they were recorded as mainly holding firelines only 16% of the time).
- Dozer and tractor-plow operators and dozer bosses generally had higher fireline-average PM4 exposures than all but the Type II(Fuels) crews, but these differences were not significant.

As was seen for CO, the right plot of Figure 32 (titled "Up.Downwind.1") confirms that persons downwind of the fire during their main fireline task were significantly more exposed to smoke than persons upwind.

For establishing similar exposure groups, estimated fireline-average exposures might be focused among Type I/I(IHC), Type II(Fuels) and Type II(IA) crews performing fireline holding and mop-up tasks in downwind situations, and among Dozer crews performing dozer operations. A long-term PM4 surveillance project might focus on tracking and assessing the effectiveness of mitigation strategies for fireline-average PM4 exposure among these crews doing these tasks in these conditions, because the model indicates that they will have the highest fireline-average PM4 exposures. By grouping future data by these crew, task and wind position categories, the inherent variability of the results may be reduced, thereby improving the ability to detect a real reduction of exposure from a given mitigation strategy.

In summary, for PM4 and respirable quartz data, an approximation of the “day+crew” factor was made from the crew name within the fire name. The number of samples of PM4 and quartz were much lower than for CO, so statistical power to detect the importance of factors was reduced, but significant factors included the crew type, the majority activity during the fireline time, and the position up- or downwind of the fire. Downwind positions had significantly higher fireline-average PM4 exposures than upwind positions. Fireline-average PM4 exposure was significantly higher among Type II(Fuels) and Type I/I(IHC) crews than among Engine(III/IV) crews. Although Type II(Fuels) crews had higher PM4 exposures than Type II(IA) and Type I/I(IHC) crews, they were not significantly higher. The PM4 exposures among Dozer(I/II/III) crews were higher than all crew types except Type II(Fuels) but were not significantly higher than any other crew type.

In terms of main activity during the shift, PM4 exposures among those doing mainly mop up were significantly higher than those doing mainly Handline/sawyer(Indirect) line construction, and those performing ancillary tasks. PM4 exposures for those doing mainly mop-up and holding fireline were also higher than Handline/sawyer(direct or indirect), and dozer operations, but not significantly so. The average PM4 exposures for those doing mainly mop up was higher, but not significantly higher than those holding firelines. PM4 exposure management implications from these findings indicate that the most effective opportunities to reduce PM4 exposures would be among Type II and Type I crews downwind of the fire, doing mop up and holding firelines. Dozer crews also present opportunities to reduce PM4 exposures.

2.4 FIRELINE-AVERAGE RESPIRABLE CRYSTALLINE SILICA EXPOSURE

There were 128 observations of respirable crystalline silica exposure among firefighters in 2010-2011 (the PM4 samples were subsequently analyzed for crystalline silica—all was found to be quartz). As for the PM4 data, for respirable quartz the lack of replication within a crew meant that “*daycrew*” could not be used as a clustering factor. For respirable quartz, the best hierarchy was obtained by using *Crew.Name* within *Fire.Name*, which produced an ICC of 0.70. This formed the null model for comparing fixed effects.

The fireline-average respirable quartz model included all 128 observations of firefighters' fireline-average respirable quartz exposure, clustered among 50 fire names, and 104 crew names within them (some crews were sampled on more than one day within a given project wildfire or PNF). Simplification dropped several factors that had been significant for CO and PM4. The final model (qtz.model1.4a) only kept the following categorical and continuous fixed-effect factors:

- Majority activity during the fireline time—(Ancillary, Dozer or tractor plow operator or dozer operations boss "DozerOps", direct handline construction and sawyer "Handline/Saw(Dir)", and indirect Handline/Saw(Ind), Holding, Lighter and lighting boss "LightingOps", and Mop up); and
- Grand mean centered percentage of time spent in the majority activity.

The interaction between activity and percentage of fireline time it represented was not significant for the quartz exposures, but it could well be in future sampling designed to test this. Crew type, Fire type and position with respect to the wind were also not significant in the model for respirable quartz exposure and were dropped. There were not enough observations of other factors to include them in the model. As for PM4, this was a three-level model, with each firefighter being nested within a given crew for a given fire. The model can be summarized as:

$$logFireline.Quartz = Activity2.1.1 + Ctr.PctFireline1$$

Where:

logFireline.Quartz = the log of the fireline-average respirable crystalline silica concentration (adjusted for the method detection limit),

Activity2.1.1 = The most-performed activity represented in the time on the fireline (for a given state of all the other final factors in the model); and

Ctr.PctFireline1 = The grand mean centered percentage of fireline time represented by the most-performed activity.

LmerTest reported a Chi-square value of 42.5 for the random effects *Fire.Name2/Crew.Name*, (probability <1e-07). Population fixed effect estimates for the model parameters are listed in Table 6;

the degrees of freedom, t-statistics and probabilities were calculated in package “lmerTest” using the Satterthwaite method of estimation.

Table 6: Least-squares means estimates for log Fireline-average respirable quartz exposure among US wildland firefighters, 2010-2011

Parameter:Category	Estimate	Std. Error	df	t value	Pr(>|t|)	Sig.
Activity2.1.1 Ancillary	-3.913	0.215	79	-18.2	<2e-16	***
Activity2.1.1 DozerOps	-2.987	0.318	92	-9.39	<2e-16	***
Activity2.1.1 Handline/Saw(Dir)	-3.936	0.465	112	-8.47	<2e-16	***
Activity2.1.1 Handline/Saw(Ind)	-3.913	0.454	99	-8.61	<2e-16	***
Activity2.1.1 Holding	-4.554	0.264	93	-17.28	<2e-16	***
Activity2.1.1 LightingOps	-4.235	0.376	98	-11.3	<2e-16	***
Activity2.1.1 Mop up	-3.350	0.239	96	-14.0	<2e-16	***

Notes: Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Model plots by explanatory factors are discussed below. As for PM4, a slightly better fit might result by fitting a curvilinear model, especially at lower concentrations of respirable quartz. Figure 33 shows the fit and observed values of the linear MLM for (log) fireline-average respirable quartz exposure by crew type, a factor that was dropped in the model. Despite not including this factor, the mixed model is a reasonably good fit among the crew types. The model tends to over-predict respirable quartz exposure for low exposures, and under-predict at high exposures.

Figure 34 shows the fireline-average respirable quartz model fit by fire type (a factor that was also dropped from the model). The model mostly under-predicts the highest respirable quartz exposures. Comments in the PM4 section above regarding the predominance of dozer operators/bosses in the initial attack factor apply equally to these quartz results.

Figure 35 shows the fireline-average respirable quartz model fit by majority task on the fireline for each firefighter, the key factor that was retained in the model. For respirable quartz samples, the firefighter’s main task averaged 45% of the fireline time. Higher exposures are mostly under-estimated by the model, and low exposures mostly overestimated.

Figure 36 shows the fireline-average respirable quartz model fit by position up- or downwind of the nearest source of smoke—a factor that was dropped from the model. Because quartz is not necessarily associated with smoke, it was not surprising that this factor was not significant in the model.

Figure 37 shows the fireline-average respirable quartz model fit versus the grand mean centered percentage of time in the main task. This factor was retained in the model, but the interaction with the specific activity was dropped from the model during simplification. The average firefighter in the group with respirable quartz data spent 45% of their fireline time in the main task, and the centering subtracted this mean from each observation. So a value of -0.4 means that the firefighter spent just 5% of their fireline time doing this main task, a value of 0 means they spent 45% of their time doing the task, and a value of 0.4 means they spent 89% of their time doing this task. As was seen for CO exposure, the more time spent performing ancillary activities, the lower the respirable quartz exposure on the fireline. There does not appear to be a trend for other activities, although due to a single point the respirable quartz exposure would appear to trend downward with increasing time spent holding line. This could represent a real effect, because holding fireline is essentially guarding the perimeter. Although while doing this firefighters are frequently exposed to smoke, they may not be exposed to much soil dust (and so quartz) because they may just be watching for incursions across the fireline ("slopovers"), and if lucky may not spend much time disturbing soils extinguishing those fire incursions. Only the latter activity would create airborne soil dust that might contain quartz. By similar logic, more time spent in mop-up would be expected to result in more respirable quartz exposure, but the model did not find a significant interaction with the percentage of time in the tasks. Soil quartz content would be expected to vary across sites, possibly confounding a relationship.

Figure 38 shows the observed and model-fitted fireline-average respirable quartz exposure by USFS Region. The factor 'Region' was dropped from the final model because it was nonsignificant. The model fit to the data was reasonably consistent across all regions of the country. Region 2 is over-predicted by the model but there were very few results there.

Figure 39 shows the contrasts among least-squares means for the levels of activity, the only significant categorical factor kept in the model. These are the differences in the means, after adjusting for the effects of other variables. From these plots we can see the 95% confidence intervals on the differences in the individual means for each level of each categorical variable (the dark line with end-hatches), and the differences in those means (the thick gray or colored bars). Red bars represent factor levels that are most significantly different (probability $p<0.001$), orange are very significantly different ($p < 0.01$), and yellow are significantly different ($p<0.05$). For the main work activity ("Activity2.1.1"):

- Ancillary tasks had lower fireline-average respirable quartz exposure than almost every other task (there were only four samples of Handline/Sawyer(Indirect), so we cannot rule out an unrepresentative sample), but only the respirable quartz exposure during dozer operations and mop-up was significantly higher than the ancillary tasks. Lending some weight to the hypothesis above of low soil dust exposure while holding line, the respirable quartz exposure during ancillary tasks was significantly higher than while holding line;

- Firefighters mainly performing dozer operations had a significantly higher fireline-average respirable quartz exposure than firefighters who were mainly holding fireline or performing lighting operations;
- As we would have guessed based on experience, respirable quartz exposure during mop-up was significantly higher than while holding line or lighting.

For establishing similar exposure groups for exposure to respirable quartz, the model results indicate that it makes sense to focus on personnel performing mop-up tasks, and although they weren't significantly higher than other tasks, the crews performing handline construction. Clearly dozer crews are likely to be a similar exposure group while performing dozer operations. A long-term respirable quartz surveillance project should track and assessing the effectiveness of mitigation strategies for fireline-average quartz exposure among these crews doing these tasks. Grouping future data into SEGs by these task categories should improve the ability to detect a real reduction of exposure from a given mitigation strategy.

In summary, for respirable quartz, the majority activity and the proportion of time it represented were the only significant factors. Those doing mainly dozer operations had higher respirable quartz exposures than all other tasks, but significantly higher than only holding, lighting and ancillary operations. Mop-up respirable quartz exposures were significantly higher than those doing mainly holding or lighting. Differences in these patterns for respirable quartz versus PM4 make sense when considering the source—respirable quartz arising only from soil disturbance, and PM4 representing mainly smoke. Management implications for respirable quartz are that dozer operations and mop up tasks present the best opportunities to control dust exposures.

2.5 EXPOSURE AT FIRE CAMPS

Data collected by the T&D Program at wildfires throughout the US between 2010 and 2012 found that highly-elevated smoke incidents in fire camps were likely to be rare. Ambient air quality was measured over 24-hour periods during 80 days at 21 incidents. Results were validated for 79 days of PM_4 measurement and 80 days of CO measurement. Table 7 summarizes these data.

Table 7. Fire Camp Ambient Air Quality Data Summary (2010–2012)

	8-Hour Maximum Ambient CO Level (ppm)		24-Hour Respirable Dust (PM_4) Level (mg/m^3)	
Parameter	**ICPs**	**Spike Camps**	**ICPs**	**Spike Camps**
KM Arithmetic Mean[1]	0.32	0.28	0.035	0.050
KM 95% UCL Mean[2]	0.60	0.46	0.049	0.069
95th Percentile Level[3]	1.2	1.2	0.165	0.172
95th Percentile UCL95[4]	3.4	3.1	0.427	0.451
Criterion: OSHA PEL[5]	50	50	NA	NA
Criterion: ACGIH TLV[6]	25	25	NA	NA
Criterion: NAAQS[7]	9	9	0.150	0.150
Estimated Results Above PEL (%)	0	0	NA	NA
95% UCL: Results Above PEL (%)	0.7	0.5	NA	NA
Estimated Results Above TLV (%)	0	0	NA	NA
95% UCL: Results Above TLV (%)	1.3	1.0	NA	NA
Estimated Results Above NAAQS (%)	0.56	0.33	5.6	5.9
95% UCL: Results Above NAAQS (%)	2.9	2.6	14	15
Geometric mean	0.031	0.056	0.0077	0.0104
Geometric Standard Deviation	9.4	6.5	6.5	5.5
Number of samples	44	36	43	36
Results below method detection limits (%)	68	69	79	78

Notes:

1. Kaplan-Meier nonparametric estimate of arithmetic mean for a lognormal distribution.
2. Upper 95th percentile confidence limit on the Kaplan-Meier estimated arithmetic mean.
3. Maximum likelihood estimate of the 95th percentile air quality parameter.
4. Maximum likelihood estimate of the upper 95th percentile confidence limit on the 95th percentile air quality parameter (the upper tolerance limit).
5. OSHA Permissible Exposure Limit for workers (not established for respirable smoke particles).
6. ACGIH TLV® for workers (not established for respirable smoke particles).
7. US Environmental Protection Agency NAAQS (9 ppm CO over 8 hours, 150 μg/m^3 PM_{10} 24-hour average). A PM_4 measurement result for smoke will be similar, but slightly lower than a corresponding PM_{10} measurement.

Abbreviations:

μg/m^3 = micrograms per cubic meter
ACGIH = American Conference of Governmental Industrial Hygienists
CO = carbon monoxide
ICP = incident command post
KM = Kaplan=Meier
mg/m^3 = milligrams per cubic meter
NAAQS = National Ambient Air Quality Standards
OSHA = Occupational Safety and Health Administration
PEL = permissible exposure limit
PM_4 = particulate matter with a median diameter of 4 μm
ppm = parts per million
TLV = threshold limit value
UCL = upper confidence level

Of the 80 days with CO data, 69 percent of the rolling 8-hour average CO exposures never rose above the detection limits of the instrumentation (about 1 ppm), and the 24-hour CO levels reached 5 ppm during only one day in one ICP, and exceeded 2 ppm at only one spike camp. Based on these data, the 95 percent upper confidence level estimate of the frequency of exceeding the 9 ppm CO NAAQS is less than 3 percent. In other words, for 100 wildfires, only three would exceed that level, and less than 0.7 percent (less than 1 in 1000) would exceed the PEL.

For PM_4, 79 percent of the 79 daily 24-hour average PM_4 results were below measurement detection limits (typically the detection limit was in the range of 14-40 μg/m^3, depending on sample duration). Using methods appropriate for censored lognormal distributions, the Kaplan-Meier estimate of the arithmetic mean of these daily average concentrations was 35 μg/m^3 in ICPs and 50 μg/m^3 in spike camps. This estimate may be biased high because of the relatively high method detection limits (censoring levels). We note that this average concentration is about equal to the $PM_{2.5}$ NAAQS, and we have the understanding that these were fire camps that did not report unusually smoky or concerning conditions.

The 95th percentile estimate of the arithmetic mean was 49 μg/m^3 in ICPs and 69 μg/m^3 in spike camps. The 95th percentiles of the daily concentrations (the upper tail of the distribution) were about 170 μg/m^3 in both types of fire camp, and the 95 percent upper confidence limit on the 95th percentile (the upper tolerance limit) was 427 μg/m^3 for ICPs and 451 μg/m^3 for spike camps. More-sensitive ambient air quality monitoring equipment might improve these estimates by greatly reducing the proportion of non-detects in the PM_4 data.

Applying the 150 µg/m^3 PM_{10} NAAQS criterion on the assumption that the $PM_{2.5}$ or PM_4 concentration will not be much lower (because smoke aerosols are in the small diameter portion of the ambient particle size distribution range), these data indicate that on average about 6 percent of fire camps would exceed the PM_{10} 24-hour NAAQS, and the 95 percent upper confidence limit for this exceedance fraction is that up to 15 percent of ICPs or spike camps would exceed it. It is apparent from these data that it is highly likely that a PM_{10} or a $PM_{2.5}$ standard will be exceeded before smoke levels exceed the CO NAAQS.

2.6 CORRELATIONS AMONG ATMOSPHERIC HAZARDS

The fireline-average data provided an opportunity to test whether results were consistent with previous work showing a relationship between CO and PM4 in smoke. The correlation is important because:

3. CO dosimetry is relatively reliable and a cost-effective method of monitoring exposure to one of the major hazards among the products of incomplete combustion;
4. Literature indicates that PM4 from wildland fire smoke is likely to represent a sufficiently significant inhalation hazard to warrant a source-specific occupational exposure limit;
5. Previous data by some researchers indicated a reasonably strong relationship between CO and PM4 levels at and near wildland fire lines; and
6. If the hazard from combustion-derived PM4 can be estimated by a strong correlation to CO, this additional inhalation hazard could be estimated from dosimetry measurements aimed at the CO hazard.

2.6.1 Data Selection for Correlation Analysis

After noting consistently positive deviations above the CO vs. adjusted PM4 trend line for tasks known to be inherently dusty (bulldozer operation, mop up, vehicle driving/riding on dusty roads, handline construction), the final regression model was focused to the extent feasible only on PM4 from smoke by explicitly omitting four outliers who were engaged in tasks that create soil dust, or who had a task where a non-fire source likely exposed them to CO from an internal combustion engine.

Three of the four outliers had high adjusted PM4 exposures considering the smoke they were exposed to. One outlier was low, but mainly performed a task that could have exposed him to small engine exhaust. The following observations we judged likely to be affected by non-smoke exposures:

- Observation 92, a firefighter who spent 19% of his fireline time in standby between periods of bulldozer operation on a shift of initial attack firefighting in Texas;
- Observation 19, who spent 77% of his fireline time mopping up;
- Observation 64, a firefighter who spent about 35% of his fireline time constructing hand line, 22% in standby and 14% mopping up; and
- Observation 22, who spent 70% of his fireline time as a handline sawyer, with a further 13% of his time in standby. So much chainsaw operation would be expected to cause significant exposure to CO emissions.

Although the PM4 data were adjusted downward for their quartz content, the available information does not define whether the soils at a given fire had much quartz in them to begin with—so soil dust could still contribute respirable mass despite not having measurable quartz. After applying the exclusions above, the records used in the regression were reduced to 72, across 12 routinely-performed tasks. As discussed in Section 2.2 above, the task discussion below is based on the tasks that constituted the highest percentage of fireline time, but may not include all tasks contributing to CO or PM4 exposure.

2.6.2 Model Results

The relationship between CO and quartz-corrected respirable particulate matter (adjusted PM4) can be summarized as a simple linear regression:

$$Adjusted.PM4 = 0.31\ (\pm 0.06) + 0.085\ (\pm 0.0073)\ \times COPPM$$

Where:

Adjusted.PM4 = the soil-corrected PM4 exposure of the firefighter (in milligrams per cubic meter, adjusted by subtracting the respirable quartz in the respirable particulate matter samples); and

COPPM = the TWA CO exposure of the firefighter (in parts per million) over the period corresponding to the PM4 sample.

Standard model output is below. The adjusted r^2 is reasonably good for such diverse data.

```
Coefficients:
              Estimate  Std. Error t value   Pr(>|t|)
(Intercept)   0.309788  0.056233   5.509     5.45e-07 ***
```

```
COPPM                    0.084935  0.007312  11.616        < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3386 on 71 degrees of freedom
Multiple R-squared:  0.6552,    Adjusted R-squared:  0.6504
F-statistic: 134.9 on 1 and 71 DF, p-value: < 2.2e-16
```

The intercept and slope were both highly significant.

Figure 40 shows the correlation between fireline-average PM4 exposure (adjusted by subtracting any detected respirable quartz) versus the corresponding CO exposure during the same period, by main work activity. The regression includes the upper and lower 95% prediction confidence intervals. The black circles indicate data used in the regression (values above 1.2 ppm CO, and omitting the four outliers discussed above). Omitted data are shown as open circles for reference. The observations where the model was not a good fit were mainly inherently dusty tasks such as mop up, hand construction of fireline and bulldozer operation, all tasks where dust was likely to contribute to PM4 exposure. Holding fireline is expected to be among the tasks least-affected by soil dust, because the firefighters mainly stand in areas where smoke and embers are most likely to cross the fireline—they frequently do not cause much soil disturbance unless the fire makes a significant run at their perimeter area. Considering the diversity of tasks, locations and soil conditions involved, the correlation appears reasonably good as an estimating tool.

Figure 41 shows the same data by USFS Region. Because no region's data appear fundamentally divergent from with the correlation and all are mainly within the 95% prediction intervals, the regression seems reasonably consistent across the regions of the US where data were collected. At this time there are insufficient data across a wide enough range to perform a meaningful quantitative test of whether the regression varies significantly across regions or fuel models.

We do observe that the results here are similar to the regression of CO vs PM3.5 (an older OSHA size-selective cutpoint essentially equal to PM4) developed over 162 shorter-duration samples at prescribed burns in the Northwestern US by Reinhardt and Ottmar (2004).[13] That (variance-weighted) linear relationship covered CO concentrations up to about 100 ppm, and the resulting regression line was:

$$\text{PM3.5 (in mg/m}^3\text{)} = -0.03\ (\pm 0.04) + 0.114\ (\pm\ 0.005) \times \text{CO (in ppm)}$$

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[13] Timothy E. Reinhardt and Roger D. Ottmar. Baseline Measurements of Smoke Exposure Among Wildland Firefighters. *Journal of Occupational and Environmental Hygiene* 1:593-606, 2004

The coefficients from that regression are similar to those reported in the current data. Omitting observation 111 in our current data (a point with substantial leverage based on model diagnostics) would lead to a higher slope (0.096) and lower intercept (0.26), both closer to the 2004 regression, but the adjusted r^2 drops to 0.60. The 2004 work did not have silica data to enable adjusting the particulate matter for the quartz from soils, despite also having dusty tasks like mop up and fireline construction during direct attack of slop-overs. It would be useful to compare the two regressions in a combined analysis, using the earlier data from the PNW Research Paper.[14] Work by Adetona and others with USFS prescribed burning crews at the Savannah River Site in the southeastern US found a statistically-significant relationship between CO and a slightly smaller-diameter fraction of particulate matter common in public health studies (fine particles, with a 50% aerodynamic cutpoint of 2.5 microns, referred to as PM2.5).[15] They found a correlation between CO and PM2.5 in their study. Though they did not provide a linear equation, the slope appears to be substantially steeper (more PM2.5 for a given amount of CO). Their data did not obtain quartz or another measure of the contribution of soil to the observed concentration, so that could contribute to both observed variability and measured mass. Based on the current data reported here, CO continues to be a useful predictor of PM4 exposure from smoke, across all US regions. Total PM4 exposure is likely to be higher than PM4 from smoke, by an amount proportional to the respirable dust contribution from task-generated soil dust.

The best approach to determining exposure to the smoke-derived PM4 might be a sampling method that excluded non-smoke PM4. In our opinion, a good candidate for this may be to adopt an organic/elemental carbon method focusing on PM1, such as the diesel particulate matter method used by the Mine Safety and Health Administration for mining workplaces (which is essentially NIOSH Method 5040). Such a measurement requires an integrated air sample over relatively long durations, and subsequent laboratory analysis. It could still be affected by fine particulate matter derived from vehicular exhaust, small engines such as chainsaws and pumps, and drip torch emissions.

In summary, we recognized that PM4 at the breathing zone of the wildland firefighter would be due to two main source: smoke and soil-derived dust. Other sources of inhalation hazards may come into play at times, such as when firefighters are exposed to exhaust from diesel and gasoline engine operation and smoke from drip torches and fusees. We were able to adjust the PM4 concentration

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[14] Timothy E. Reinhardt, Roger D. Ottmar, and Andrew J.S. Hanneman. Smoke Exposure Among Firefighters at Prescribed Burns in the Pacific Northwest. PNW-RP-526. USDA Forest Service, Pacific Northwest Research Station. October, 2000

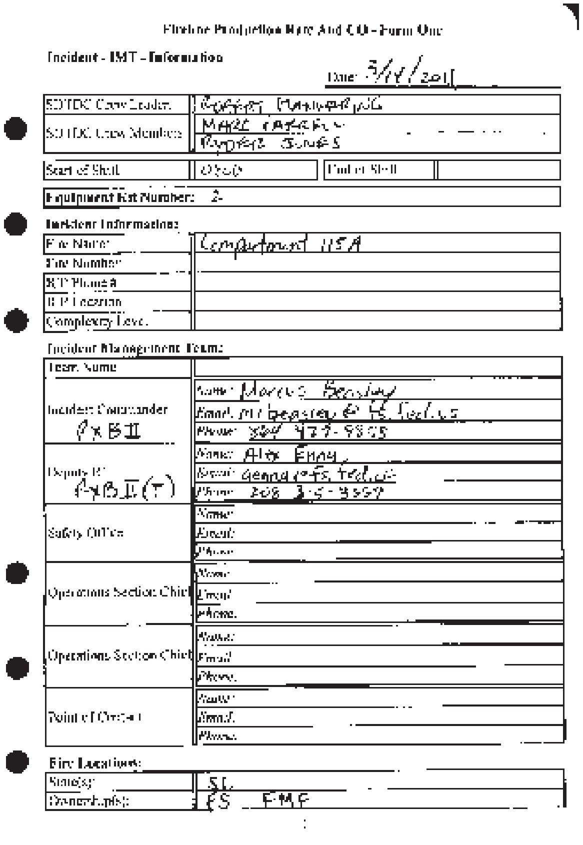
[15] Adetona, Olorunfemi, Kevin Dunn, Daniel B. Hall, Gary Achtemeier, Allison Stock, and Luke P. Naeher. Personal PM2.5 Exposure Among Wildland Firefighters Working at Prescribed Forest Burns in Southeastern United States. Journal of Occupational and Environmental Hygiene, 8(8): 503-511, 2011.

downward to correct for soil quartz by subtracting the mass of quartz measured in the sample. This likely represents the minimum effect of soil dust, because soils may not always include quartz. From this analysis, there appears to be a reasonably consistent correlation between exposure to PM4 from smoke and exposure to CO.

Especially for tasks such as holding line, where almost all the CO and PM4 are due to the fire, the CO to adjusted PM4 exposure relationship is a valuable estimator of how much of the PM4 is due to fire emissions. Should toxicology and risk assessment identify PM4 from smoke as the critical pollutant to manage, this relationship is a ready means to estimate the PM4 exposure. When tasks generate soil dust, the total PM4 exposure will reflect the additional respirable portion of the dust created by these tasks (such as mop up, handline construction, bulldozer operations, hiking in dusty conditions, and driving on dusty roads). With the recent reduction of the OSHA respirable crystalline silica standard to 0.05 µg/m^3, attention to that soil dust hazard is warranted where soils contain quartz or other forms of crystalline silica. But for estimating exposure to fire-derived PM4, these data show a reasonably strong relationship over all USFS regions and during most tasks.

Figures

Figure 1. Field Data Collection Forms



Fireline Production Rate And CO - Form One

Incident - IMT - Information

Date: 3/14/2011

SDTDC Crew Leader:	Robert [illegible]
SDTDC Crew Members:	MARC [illegible] ROBERT JONES

Start of Shift	0500	End of Shift	

Equipment Kit Number: 2

Incident Information:

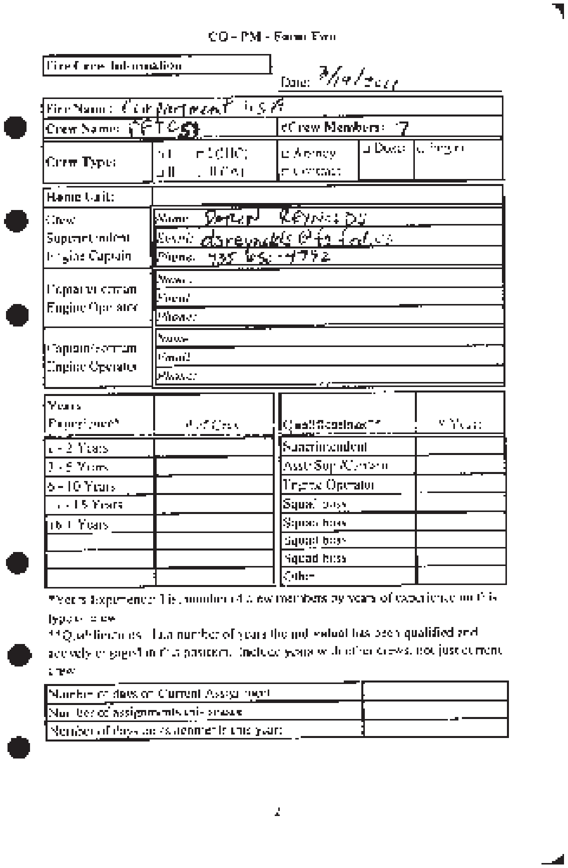
Fire Name:	Compartment USA
Fire Number:	
ICP Phone #	
ICP Location	
Complexity Level	

Incident Management Team:

Team Name	
Incident Commander [illegible] B II	Name: Marcus Beasley Email: mlbeasley@fs.fed.us Phone: 304 477-9855
Deputy IC [illegible] B II (T)	Name: Alex Enay Email: aenay@fs.fed.us Phone: 208 3 5-3557
Safety Officer	Name: Email: Phone:
Operations Section Chief	Name: Email: Phone:
Operations Section Chief	Name: Email: Phone:
Point of Contact	Name: Email: Phone:

Fire Locations:

State(s):	SL
Ownership(s):	FS FMF



CO - PM - Form Two

Fire Crew Information

Date: 3/14/2011

Fire Name: Compartment USA				
Crew Name: FFTC 51		#Crew Members: 7		
Crew Type:	☐ I ☐ 2 (IHC) ☐ II ☐ II (IA)	☐ Agency ☐ Contract	☐ Dozer	☐ Engine

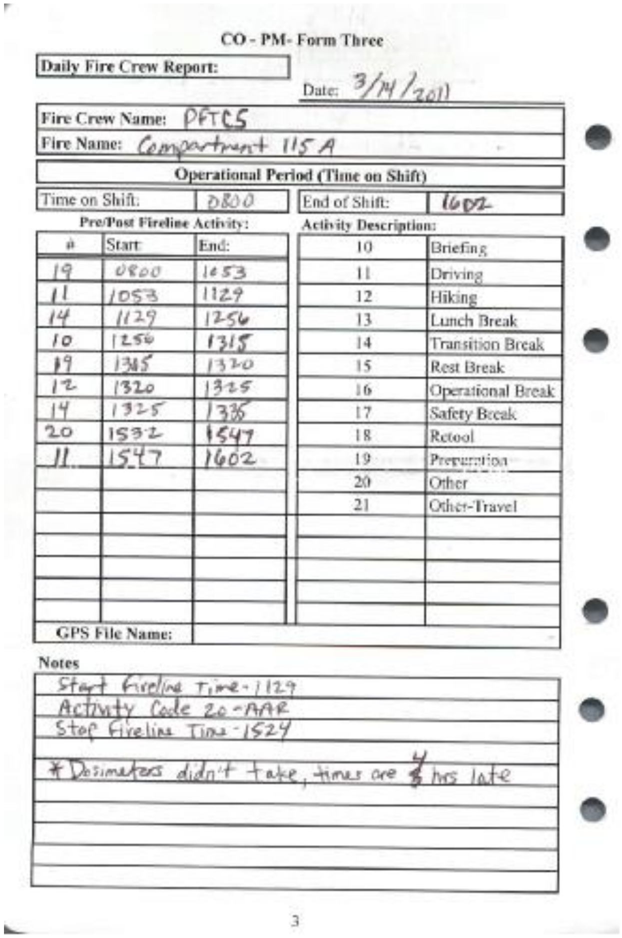
Home Unit:	
Crew Superintendent Engine Captain	Name: Darrel Reynolds Email: dreynolds@fs.fed.us Phone: 435 65 -4792
Captain/Foreman Engine Operator	Name: Email: Phone:
Captain/Foreman Engine Operator	Name: Email: Phone:

Years Experience*	# of Crew	Qualifications**	# Years
1 - 2 Years		Superintendent	
3 - 5 Years		Asst Sup /Captain	
6 - 10 Years		Engine Operator	
11 - 15 Years		Squad boss	
16 + Years		Squad boss	
		Squad boss	
		Squad boss	
		Other	

*Years Experience: The number of crew members by years of experience on this type of crew

**Qualifications: The number of years the individual has been qualified and actively engaged in this position. Include years with other crews, not just current crew

Number of days on Current Assignment	
Number of assignments this season	
Number of days on assignments this year	



CO - PM- Form Three

Daily Fire Crew Report:

Date: 3/14/2011

Fire Crew Name: PFTC5

Fire Name: Compartment 115 A

Operational Period (Time on Shift)

Time on Shift:	0800	End of Shift:	1602

Pre/Post Fireline Activity:

#	Start:	End:
19	0800	1053
11	1053	1129
14	1129	1256
10	1256	1315
19	1315	1320
12	1320	1325
14	1325	1335
20	1532	1547
11	1547	1602

Activity Description:

10	Briefing
11	Driving
12	Hiking
13	Lunch Break
14	Transition Break
15	Rest Break
16	Operational Break
17	Safety Break
18	Retool
19	Preparation
20	Other
21	Other-Travel

GPS File Name:

Notes

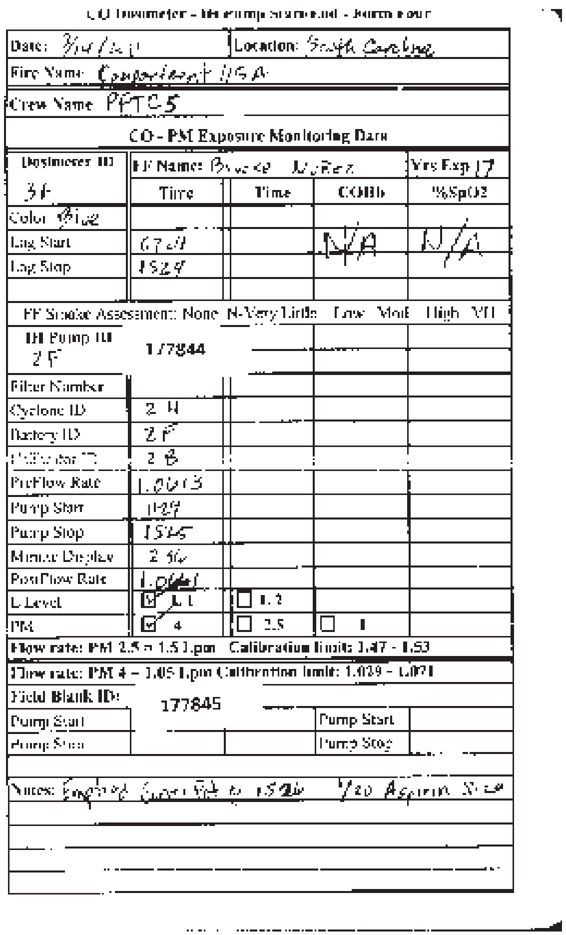
Start Fireline Time - 1129

Activity Code 20 - AAR

Stop Fireline Time - 1524

*Dosimeters didn't take, times are 4 hrs late

3



CO Dosimeter – IH Pump Standard – Form Four

Date: 3/14/11	Location: South Carolina
Fire Name: Compartment 115A	
Crew Name PFTC5	

CO - PM Exposure Monitoring Data

Dosimeter ID	FF Name: Brooke [illegible]			Yrs Exp 17
3F	Time	Time	COHb	%SpO2
Color Blue				
Log Start	0729		N/A	N/A
Log Stop	1529			

FF Smoke Assessment: None N-Very Little Low Mod High VH

IH Pump ID 2F	177844			
Filter Number				
Cyclone ID	2 H			
Battery ID	2F			
Calibrator ID	2 B			
PreFlow Rate	1.0013			
Pump Start	1129			
Pump Stop	1525			
Minute Display	2 56			
PostFlow Rate	1.0[illegible]			
L Level	☑ 1.1	☐ 1.2		
PM	☑ 4	☐ 2.5	☐ 1	

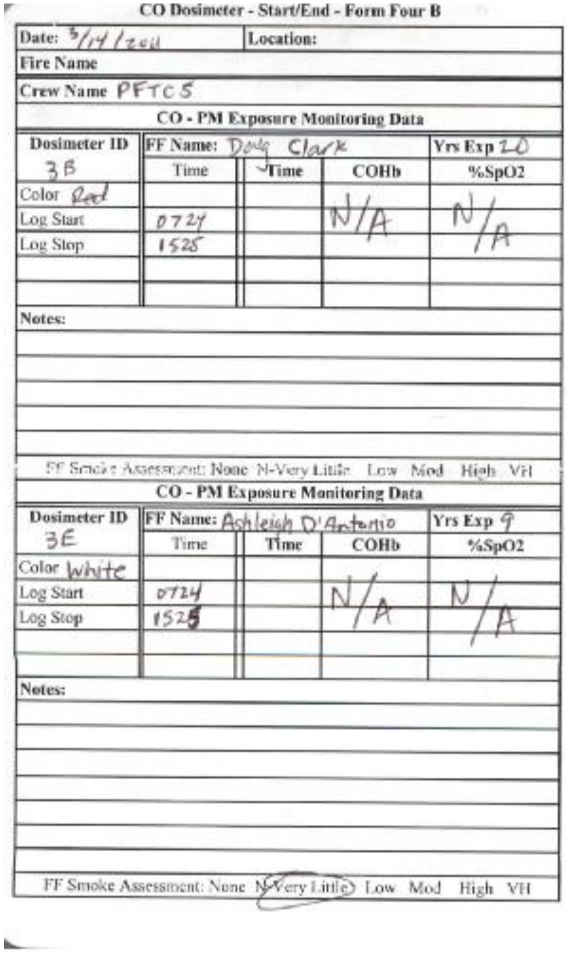
Flow rate: PM 2.5 = 1.5 Lpm Calibration limits 1.47 - 1.53

Flow rate: PM 4 – 1.05 Lpm Calibration limit: 1.029 – 1.071

Field Blank ID: 177845

Pump Start			Pump Start	
Pump Stop			Pump Stop	

Notes: [illegible] to 1526 1/20 Aspirin [illegible]



CO Dosimeter - Start/End - Form Four B

Date: 3/14/2011 **Location:**

Fire Name

Crew Name PFTC5

CO - PM Exposure Monitoring Data

Dosimeter ID 3B	**FF Name:** Doug Clark			**Yrs Exp** 20
	Time	Time	COHb	%SpO2
Color Red				
Log Start	0724		N/A	N/A
Log Stop	1525			

Notes:

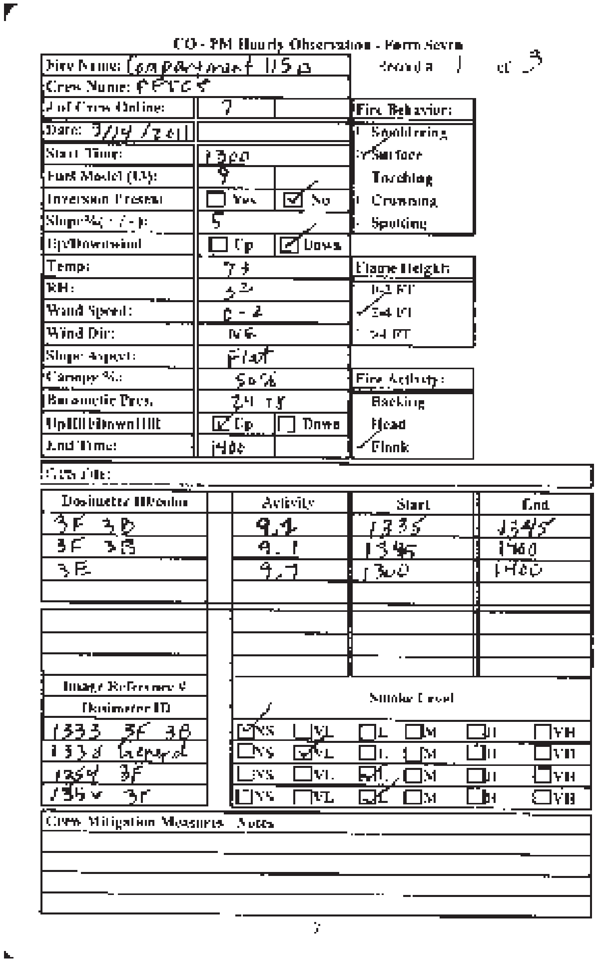
FF Smoke Assessment: None N-Very Little Low Mod High VH

CO - PM Exposure Monitoring Data

Dosimeter ID 3E	**FF Name:** Ashleigh D'Antonio			**Yrs Exp** 9
	Time	Time	COHb	%SpO2
Color White				
Log Start	0724		N/A	N/A
Log Stop	1525			

Notes:

FF Smoke Assessment: None [✓ N-Very Little] Low Mod High VH



CO - PM Hourly Observation - Form Seven

Fire Name: Compartment 115 B

Record # 1 of 3

Crew Name: PFTC5

# of Crew Online:	7	
Date: 3/14/2011		
Start Time:	1300	
Fuel Model (13):	9	
Inversion Present	☐ Yes	☑ No
Slope% (+/-):	5	
Up/Downwind	☐ Up	☑ Down
Temp:	74	
RH:	32	
Wind Speed:	0 - 2	
Wind Dir:	NE	
Slope Aspect:	Flat	
Canopy %:	50%	
Barometric Pres.	29 18	
Up Hill/Down Hill	☑ Up	☐ Down
End Time:	1400	

Fire Behavior:
- Smoldering
- ✓ Surface
- Torching
- Crowning
- Spotting

Flame Height:
- 0-2 FT
- ✓ 2-4 FT
- > 4 FT

Fire Activity:
- Backing
- Head
- ✓ Flank

Crew Job:

Dosimeter ID/Radio	Activity	Start	End
3F 3B	9.1	1335	1345
3F 3B	9.1	1345	1400
3E	9.7	1300	1400

Image Reference # / Dosimeter ID	Smoke Level					
1333 3F 3B	☑ NS	☐ VL	☐ L	☐ M	☐ H	☐ VH
1338 General	☐ NS	☑ VL	☐ L	☐ M	☐ H	☐ VH
1354 3F	☐ NS	☐ VL	☑ L	☐ M	☐ H	☐ VH
1356 3F	☐ NS	☐ VL	☑ L	☐ M	☐ H	☐ VH

Crew Mitigation Measures - Notes

7

Figure 2. Shift and fireline durations observed among U.S. Wildland Firefighters, 2009-2012

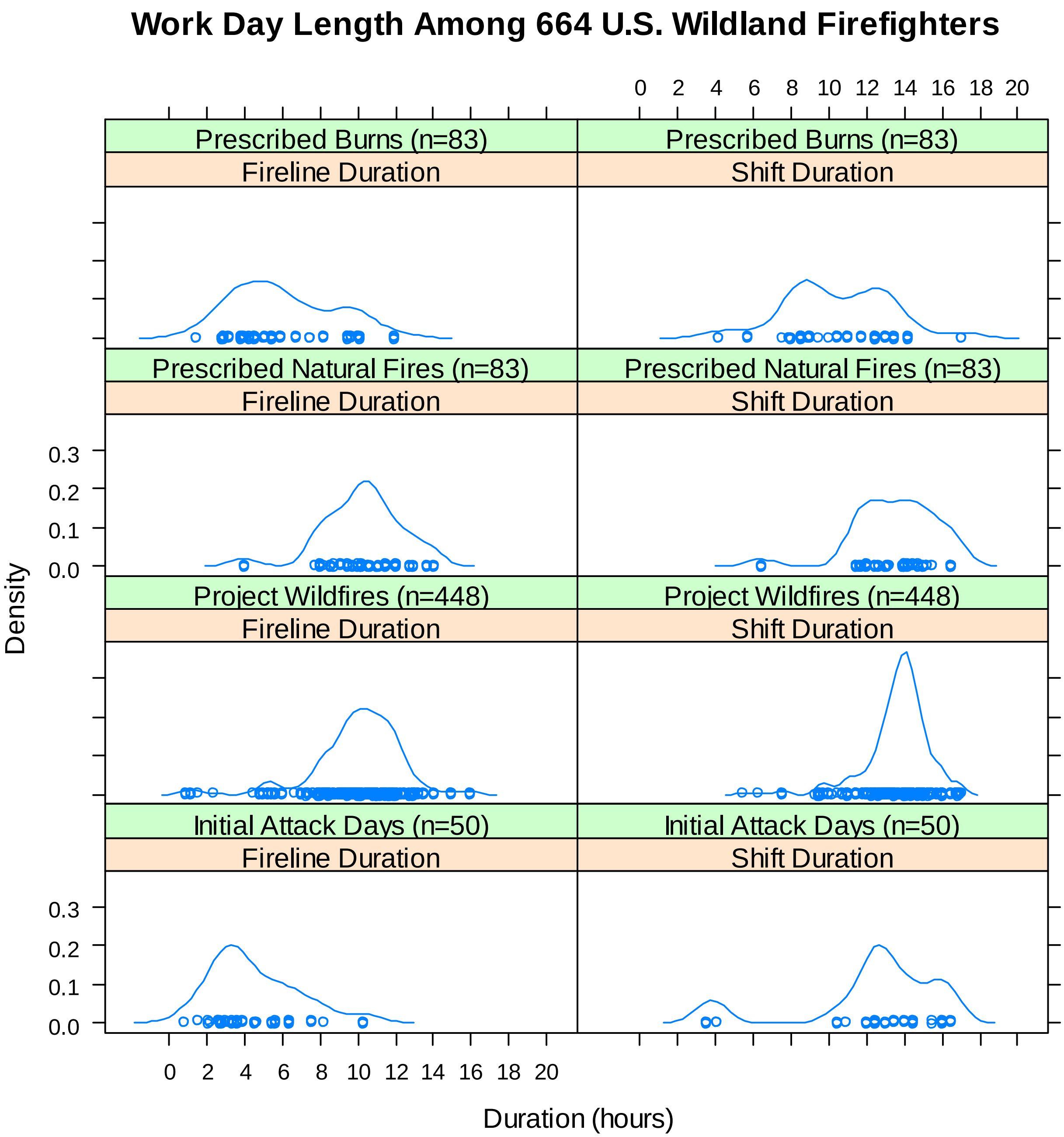


Figure 3. Maximum 1-minute average CO exposure by fire type

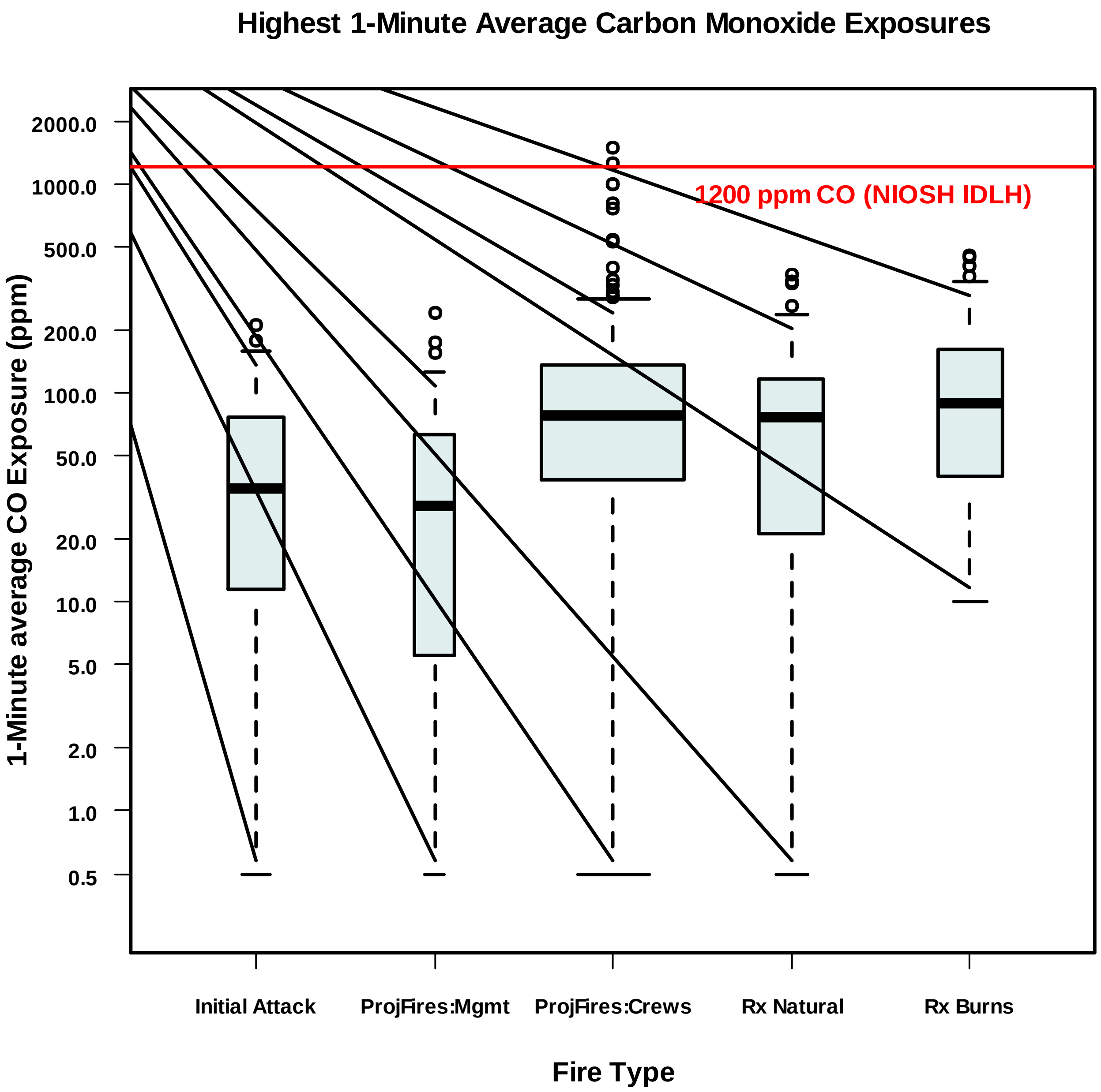


Figure 4. Maximum 5-minute average CO exposure by fire type

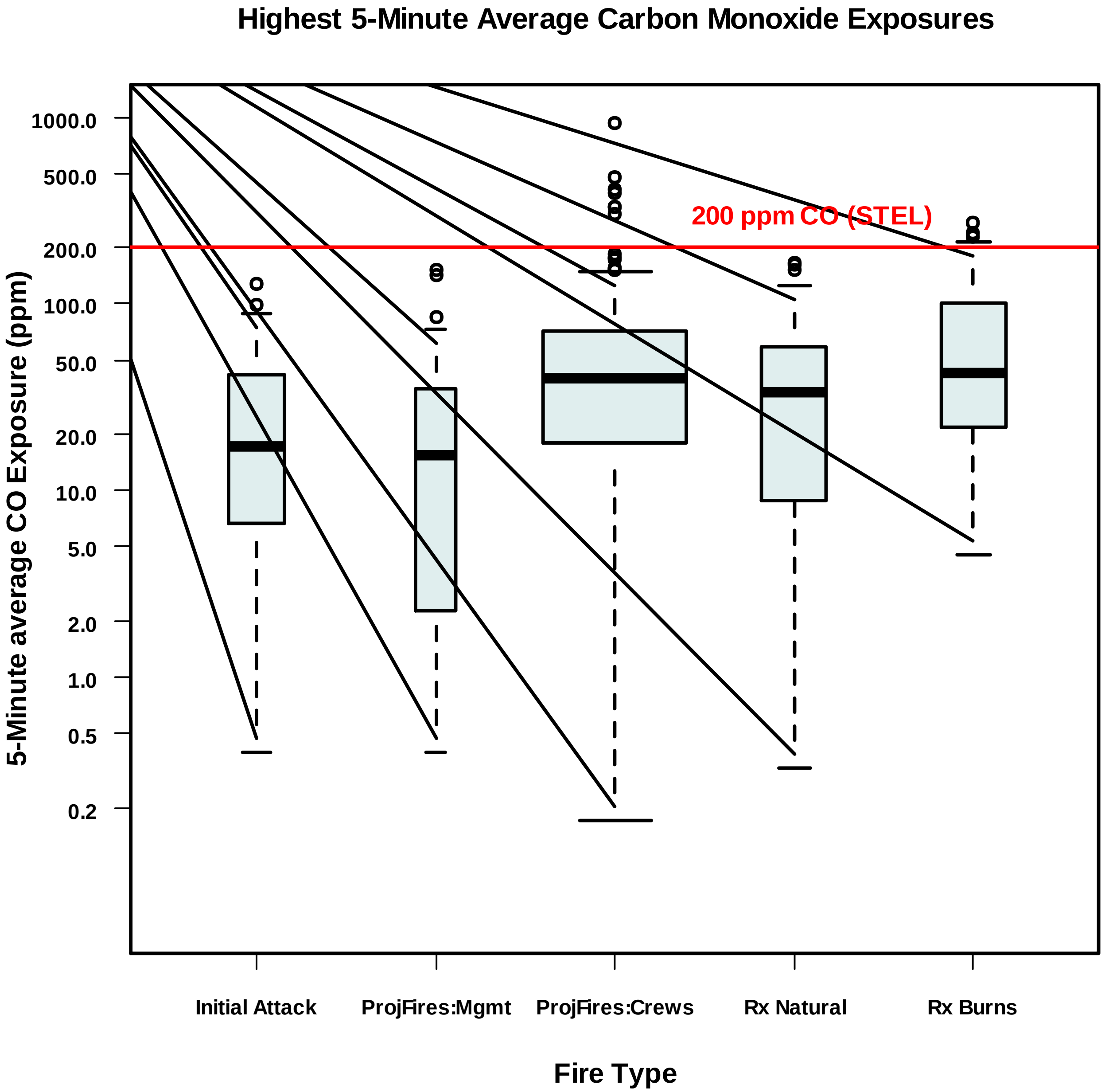


Figure 5. Maximum 8-hour average CO exposure by fire type

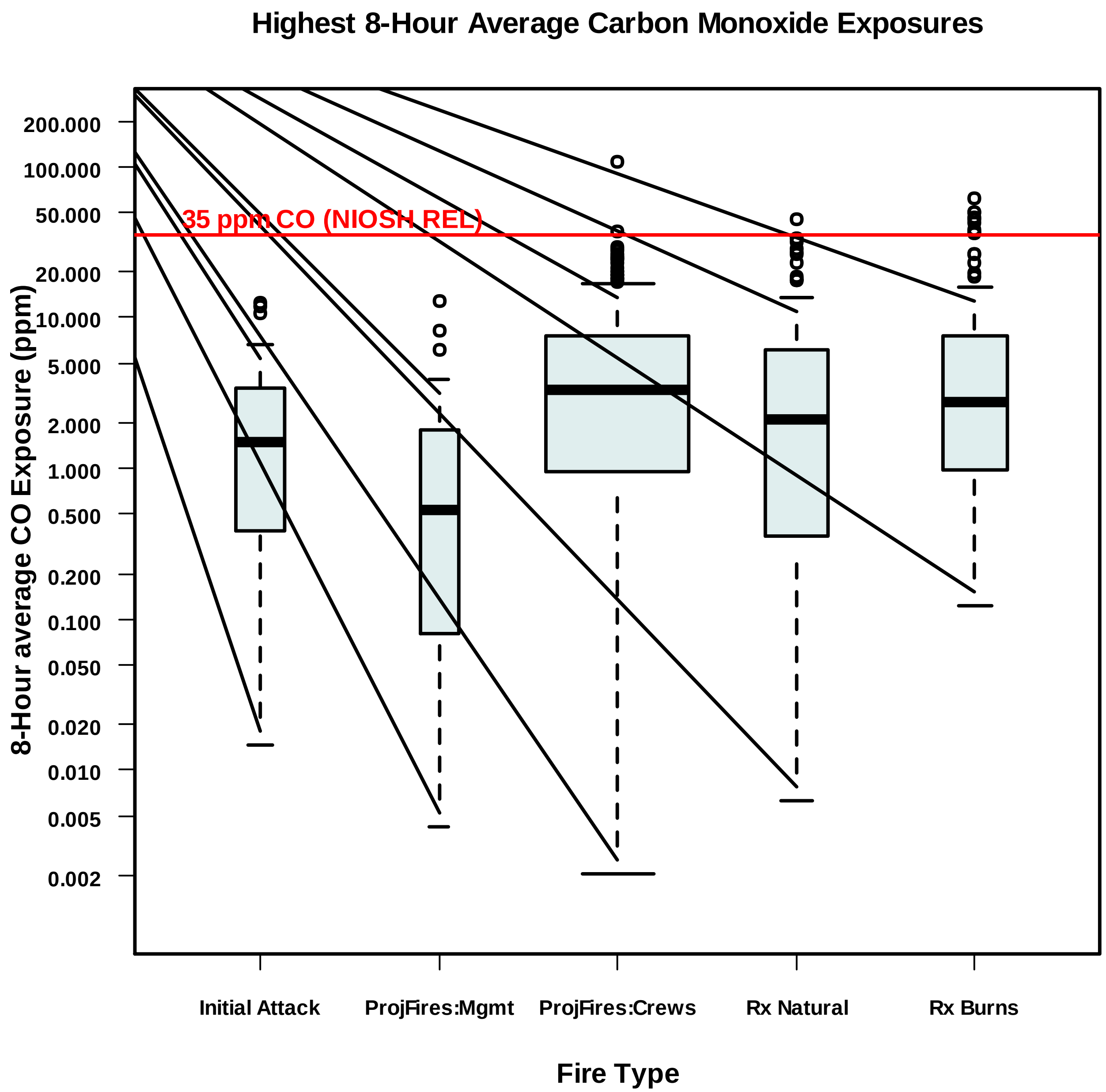


Figure 6. Maximum fireline-average CO exposure by fire type

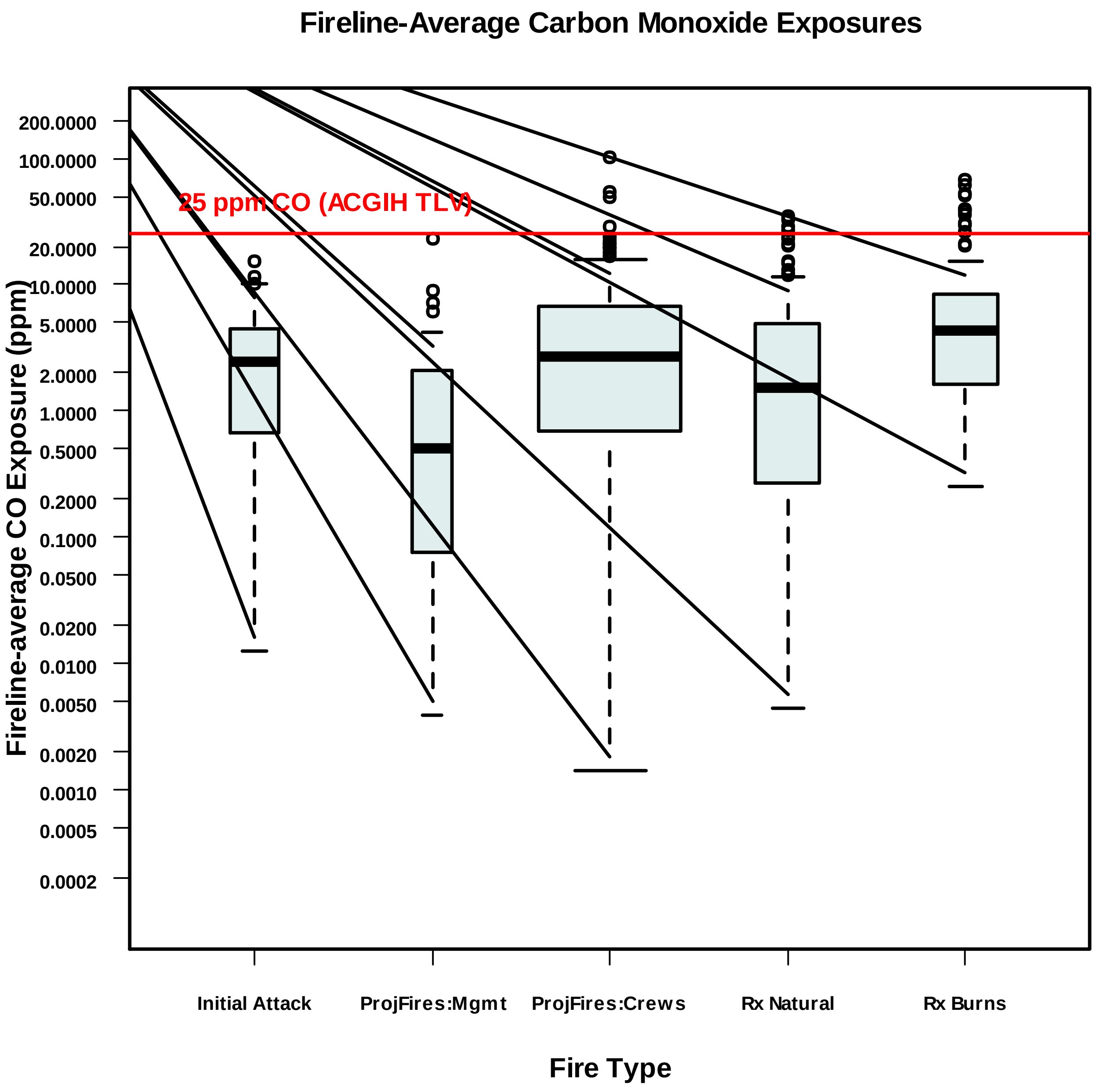


Figure 7. Maximum shift-average CO exposure by fire type

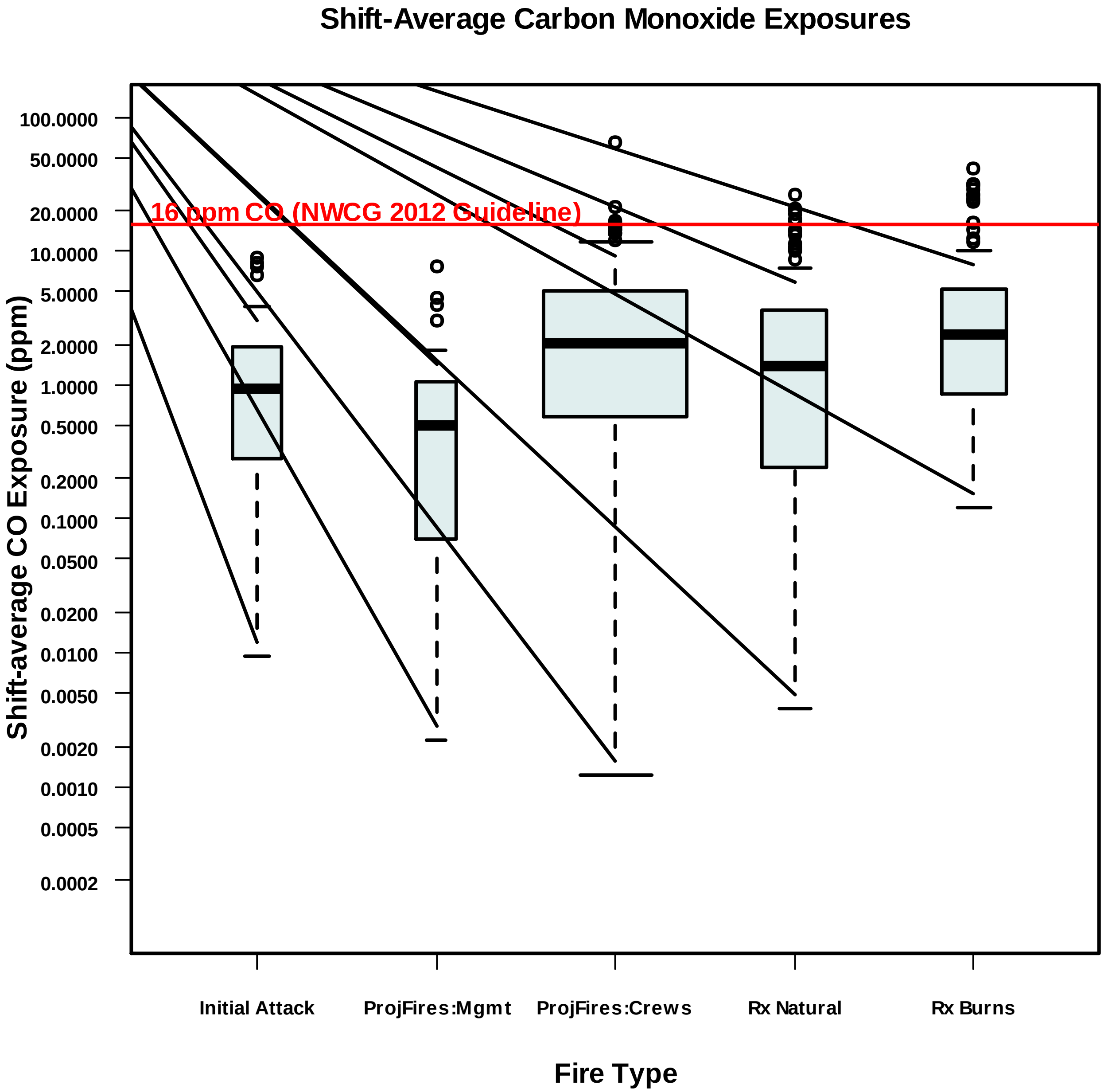


Figure 8. Fireline-average respirable particulate matter exposure by fire type

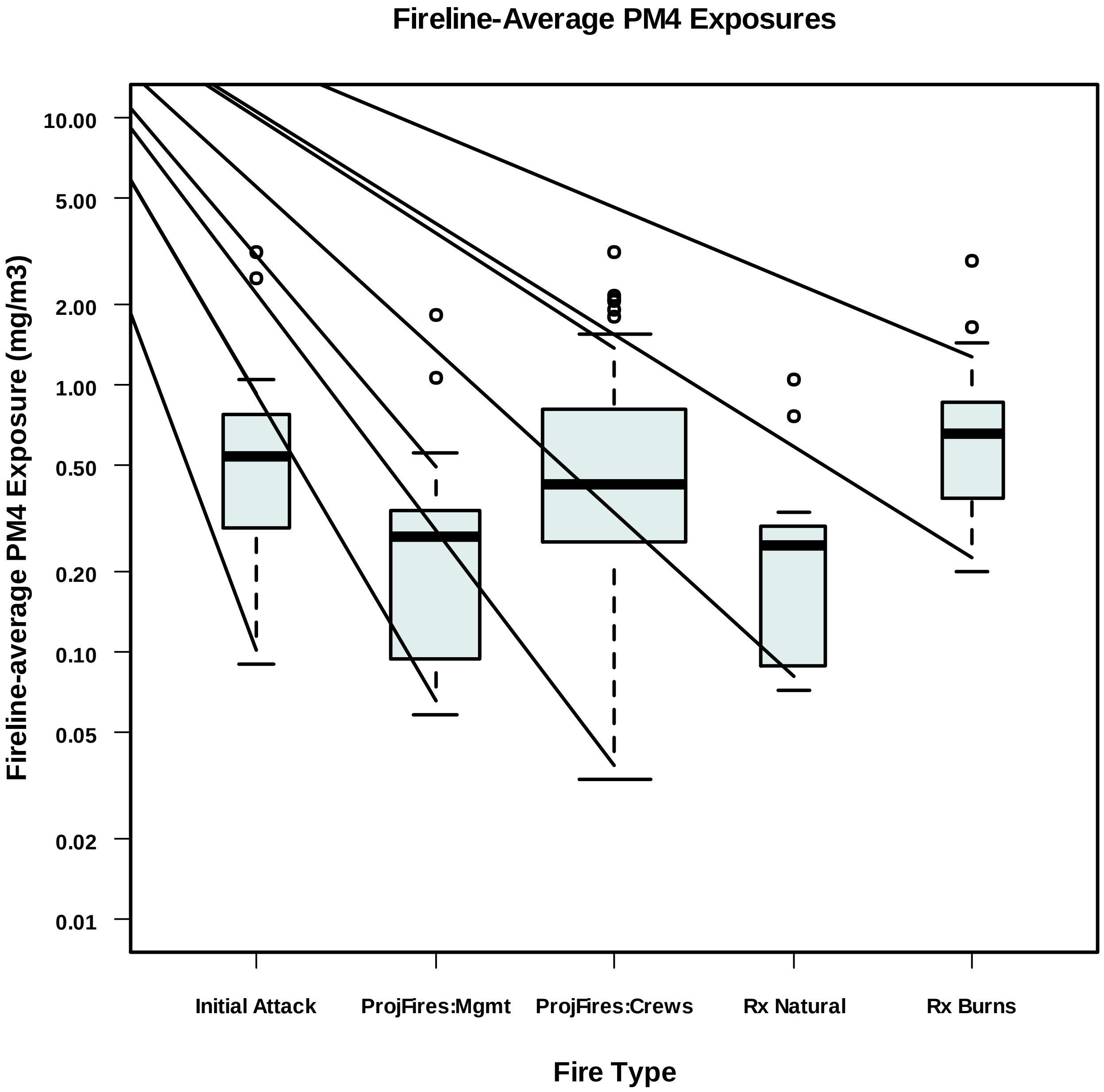


Figure 9. Shift-average respirable particulate matter exposure by fire type

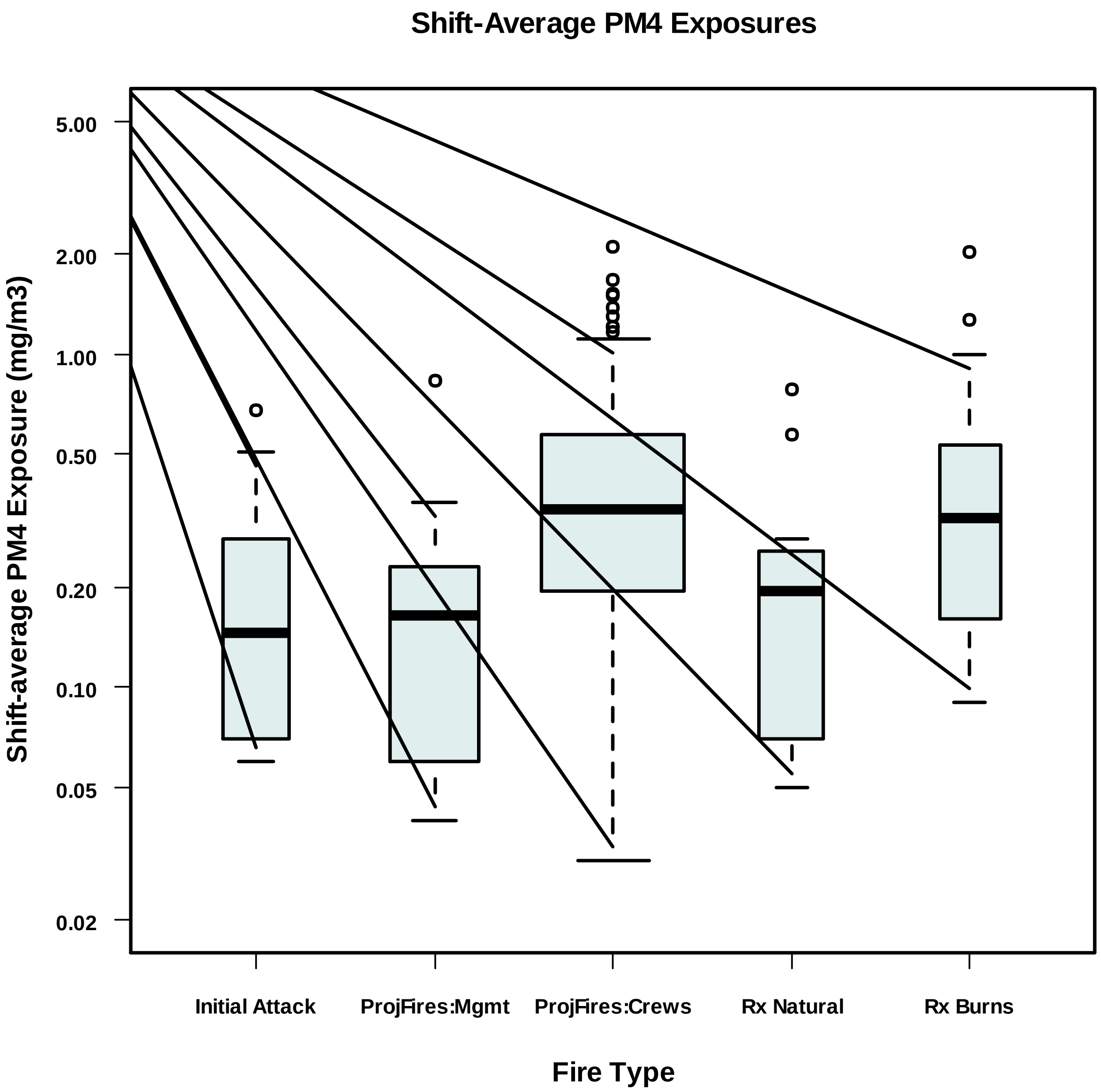


Figure 10. Fireline-average respirable quartz exposure by fire type

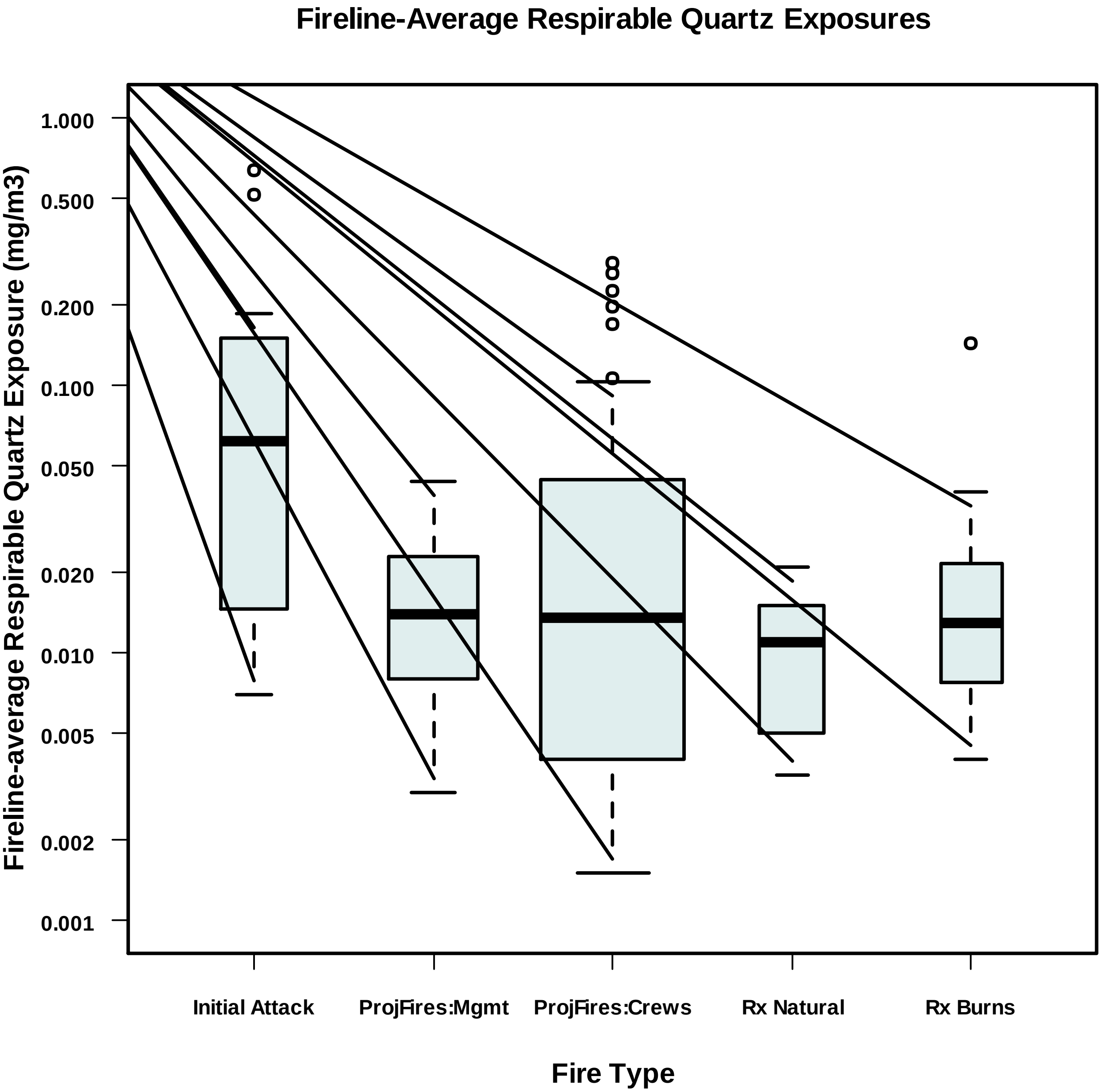


Figure 11. Shift-average respirable quartz exposure by fire type

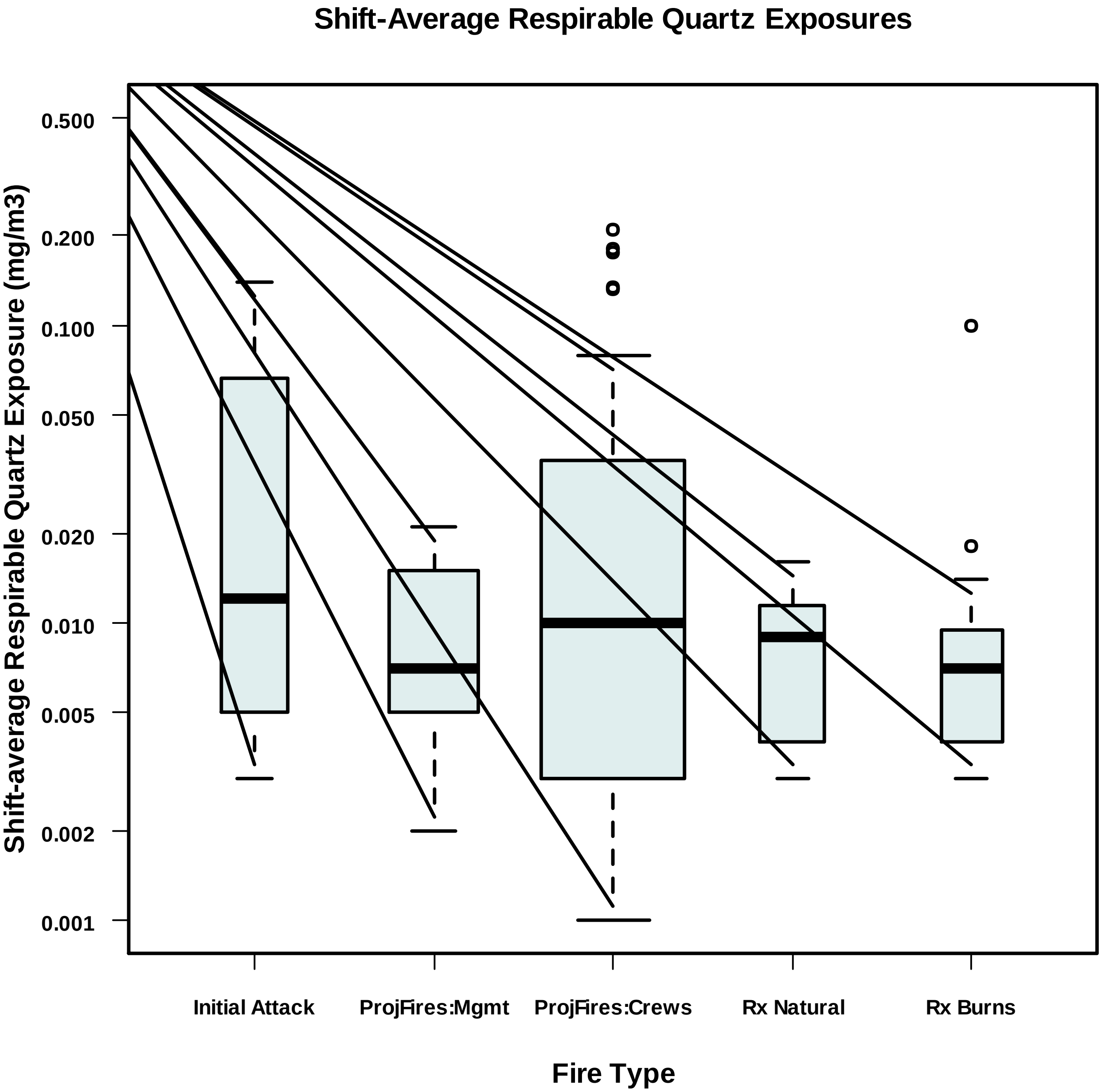


Figure 12. Shift-average respirable quartz exposure by fire type as a percent of workshift PEL

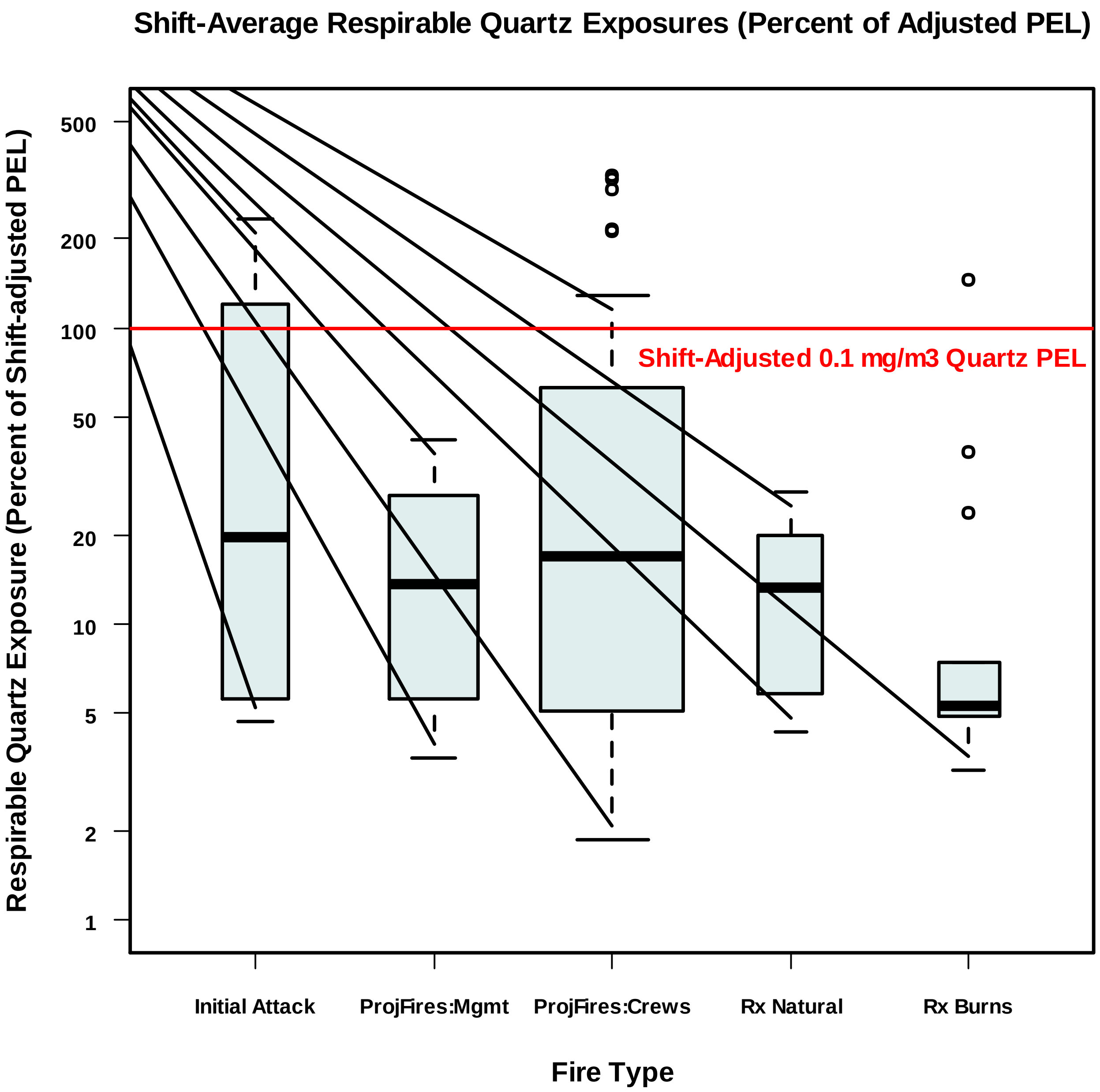


Figure 13. Modeled maximum 5-minute average carbon monoxide exposure by crew type

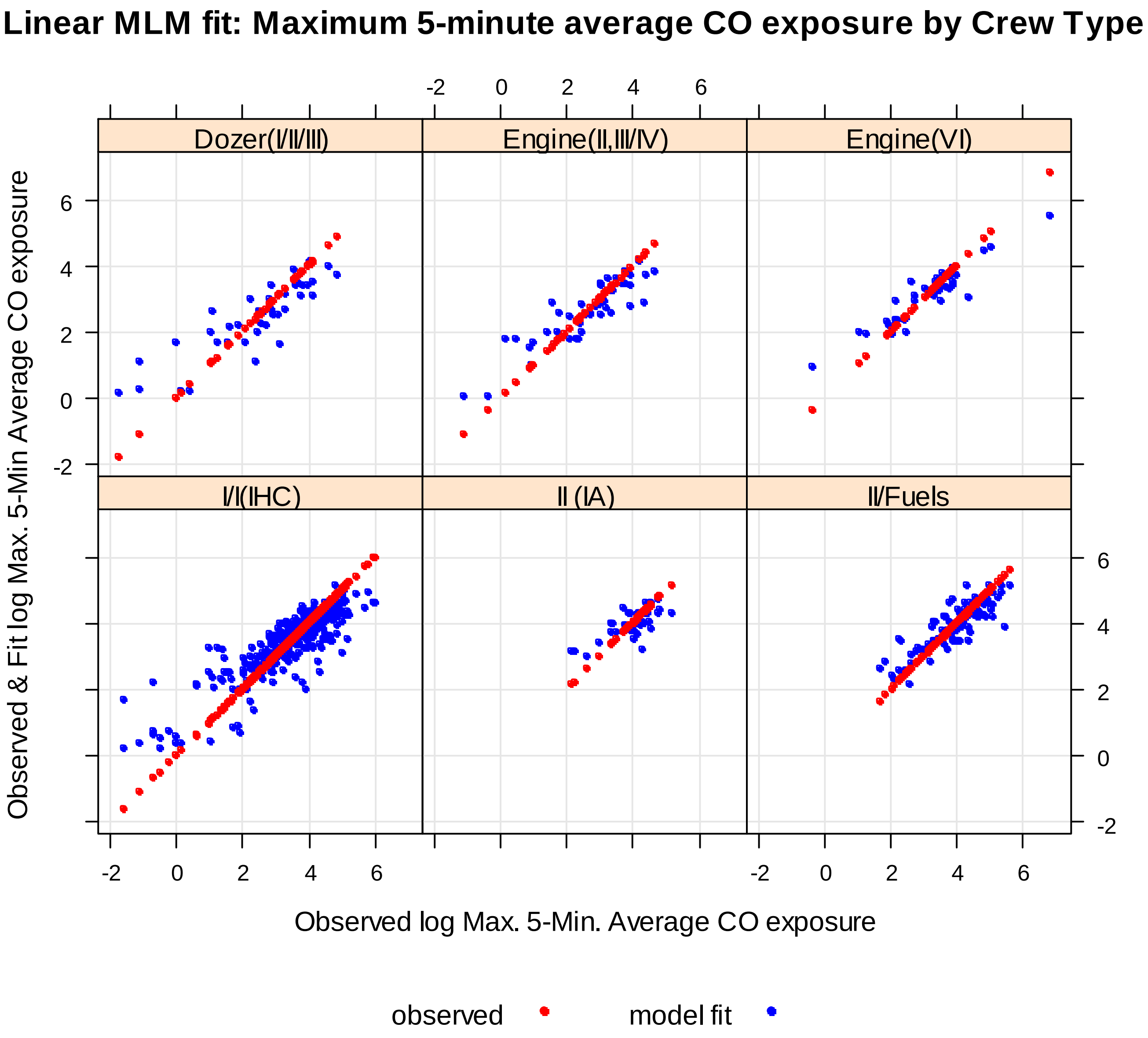


Figure 14. Modeled maximum 5-minute average carbon monoxide exposure by work activity

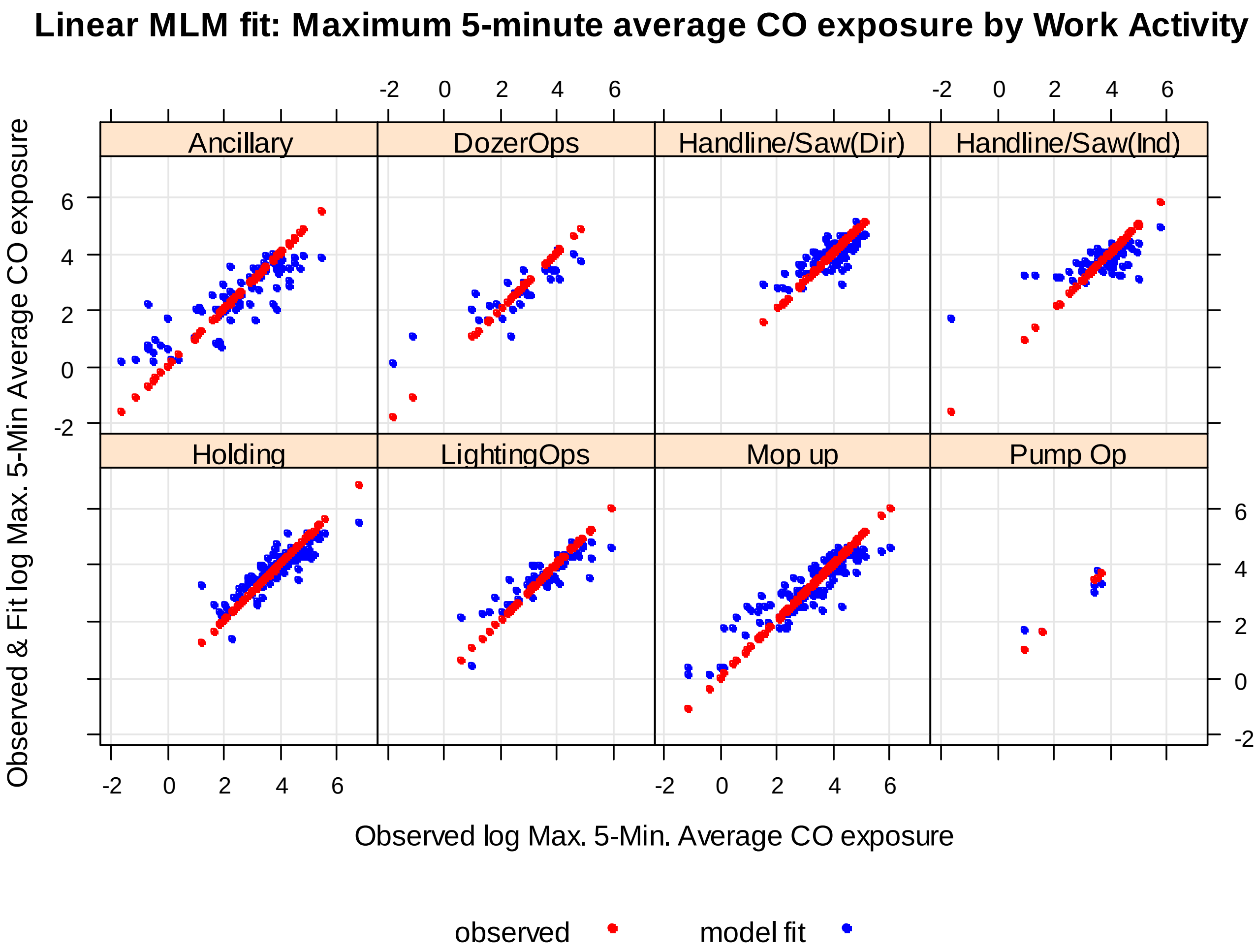


Figure 15. Modeled maximum 5-minute average carbon monoxide exposure by work activity and centered wind speed

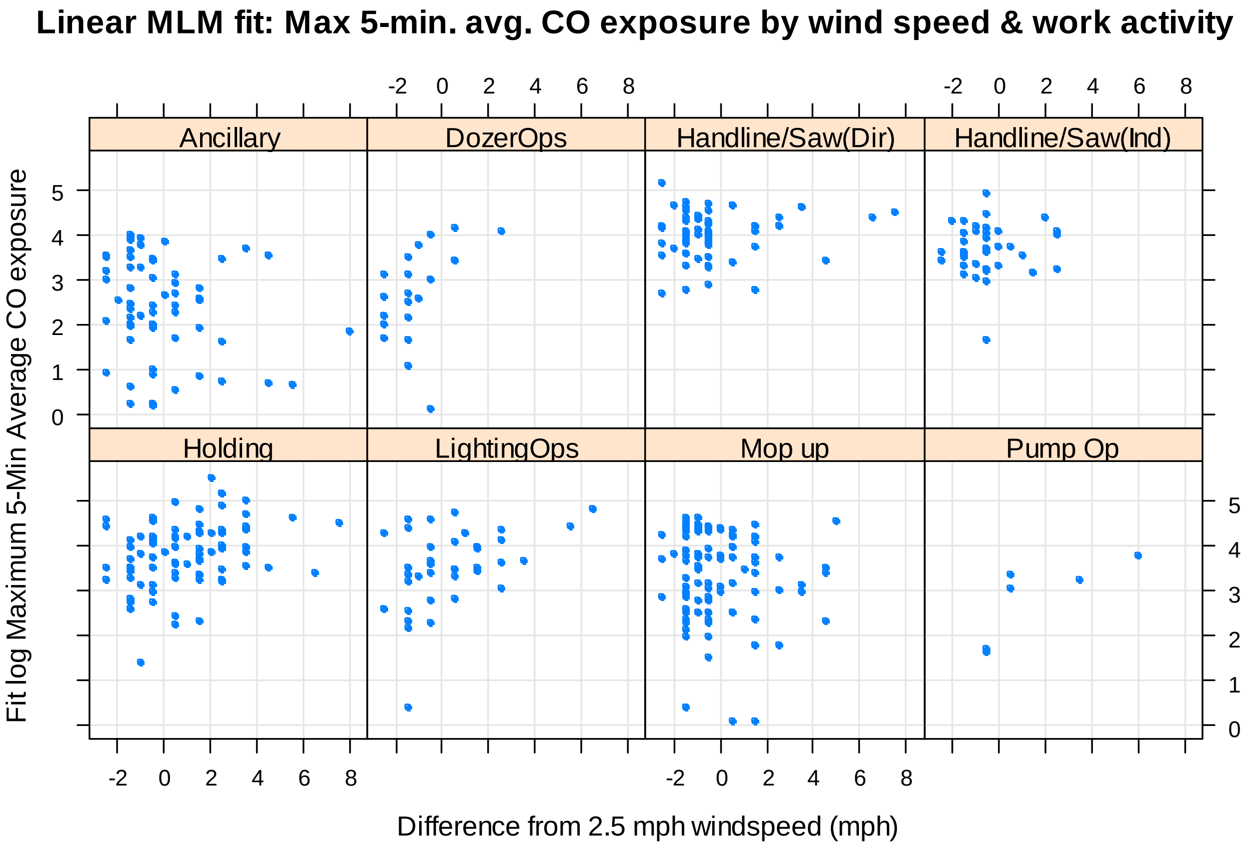


Figure 16. Modeled maximum 5-minute average carbon monoxide exposure by fire type

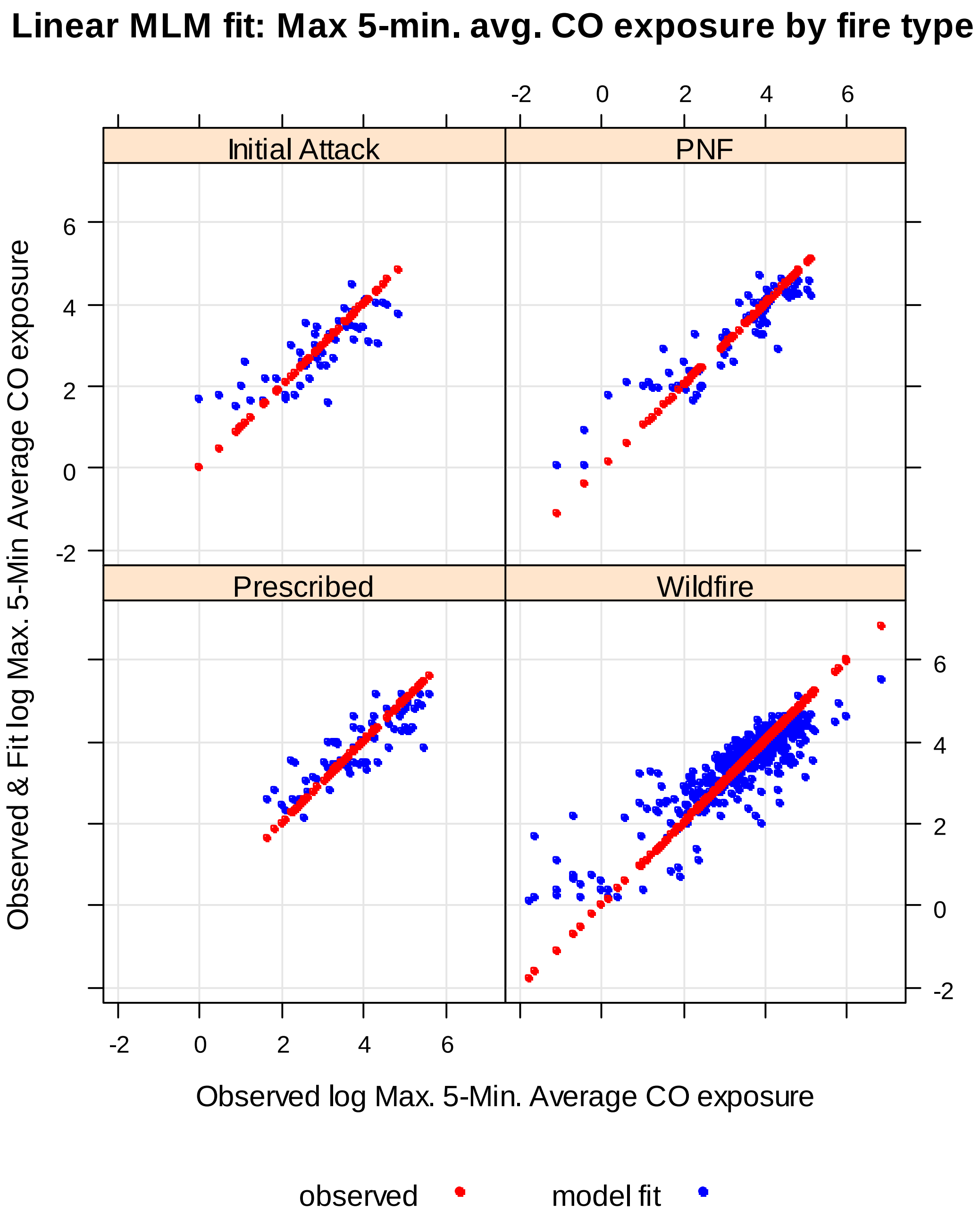


Figure 17. Modeled maximum 5-minute average carbon monoxide exposure by USFS region

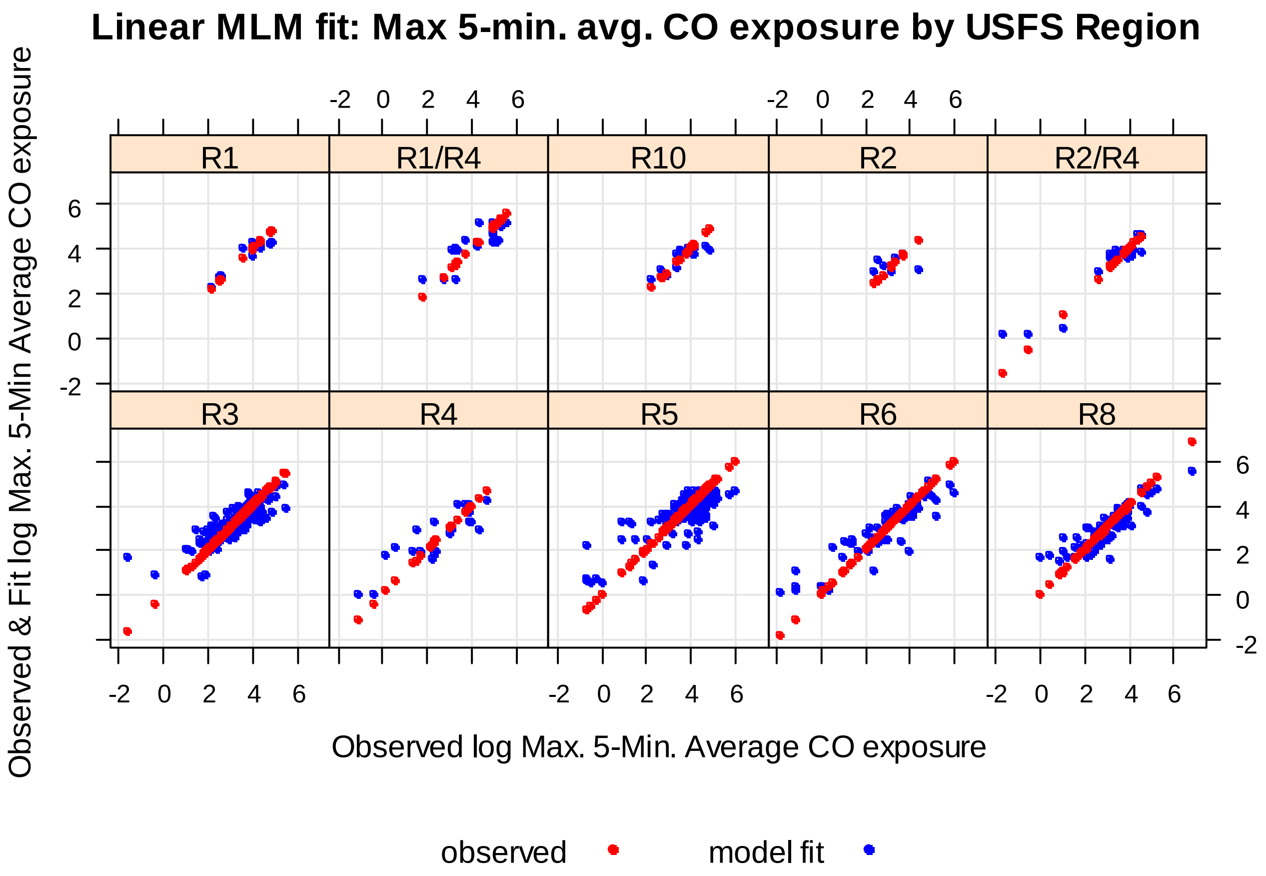


Figure 18. Contrast of maximum 5-minute average carbon monoxide exposure means

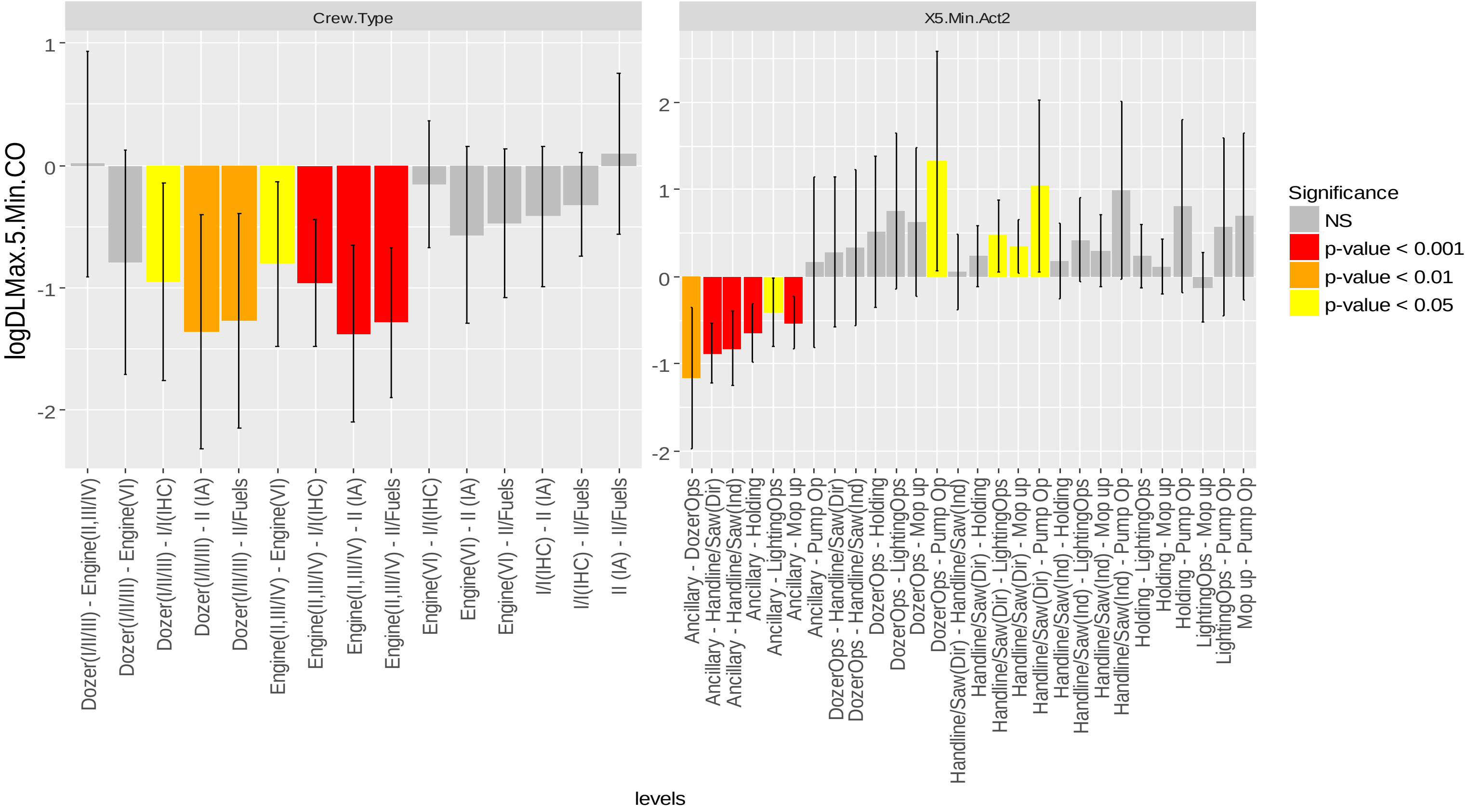


Figure 19. Modeled fireline-average carbon monoxide exposure by crew type

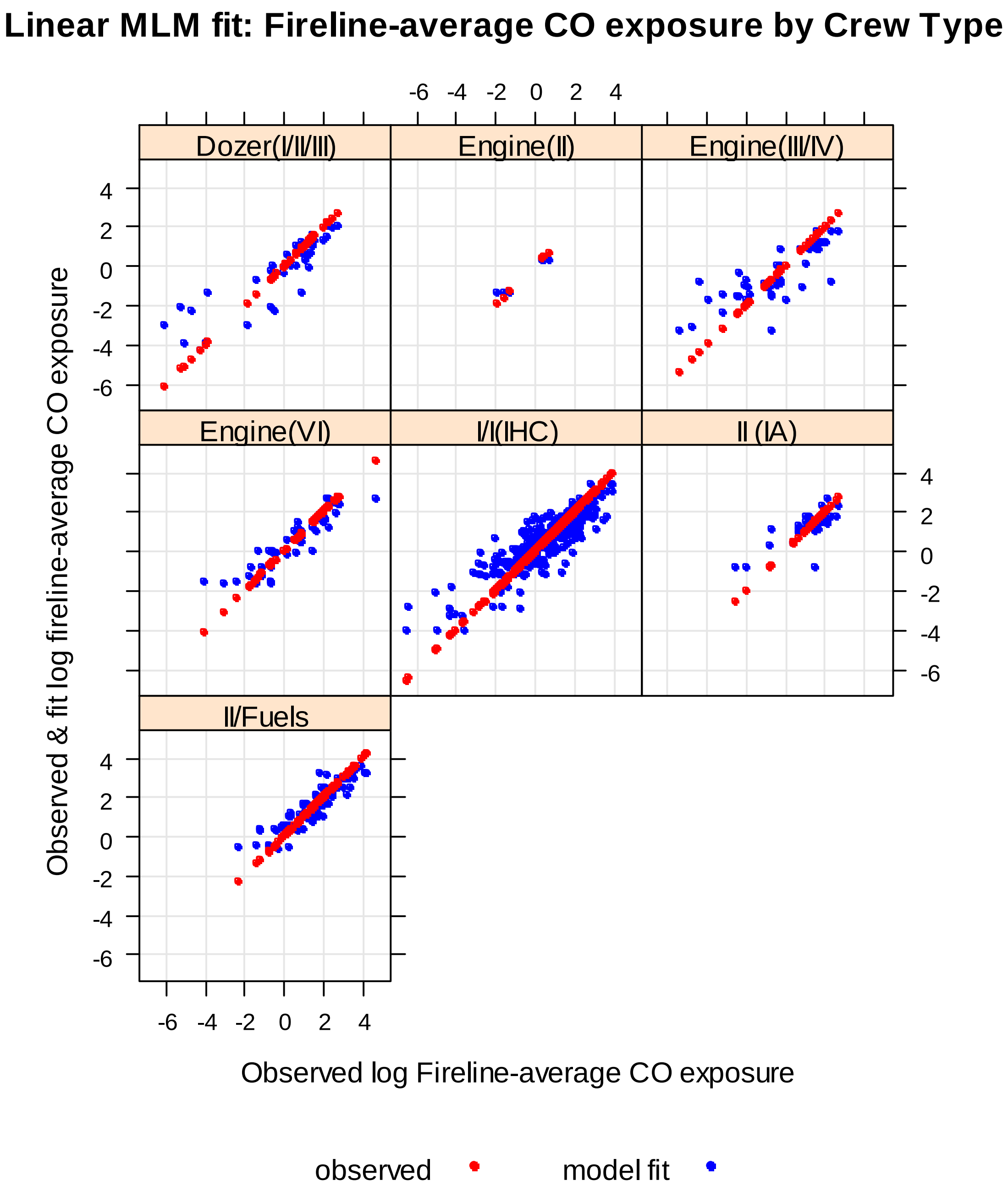


Figure 20. Modeled fireline-average carbon monoxide exposure by fire type

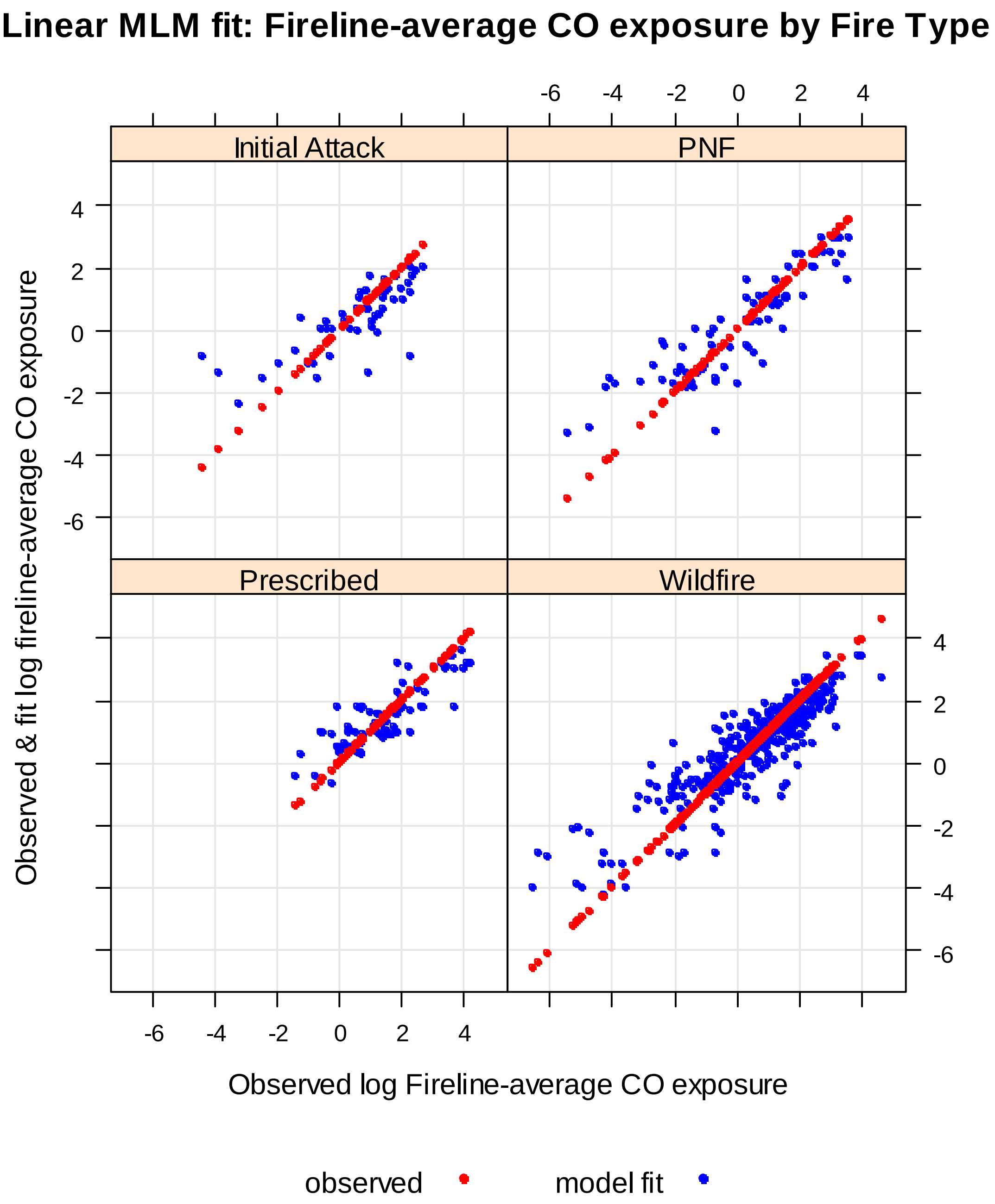


Figure 21. Modeled fireline-average carbon monoxide exposure by main task

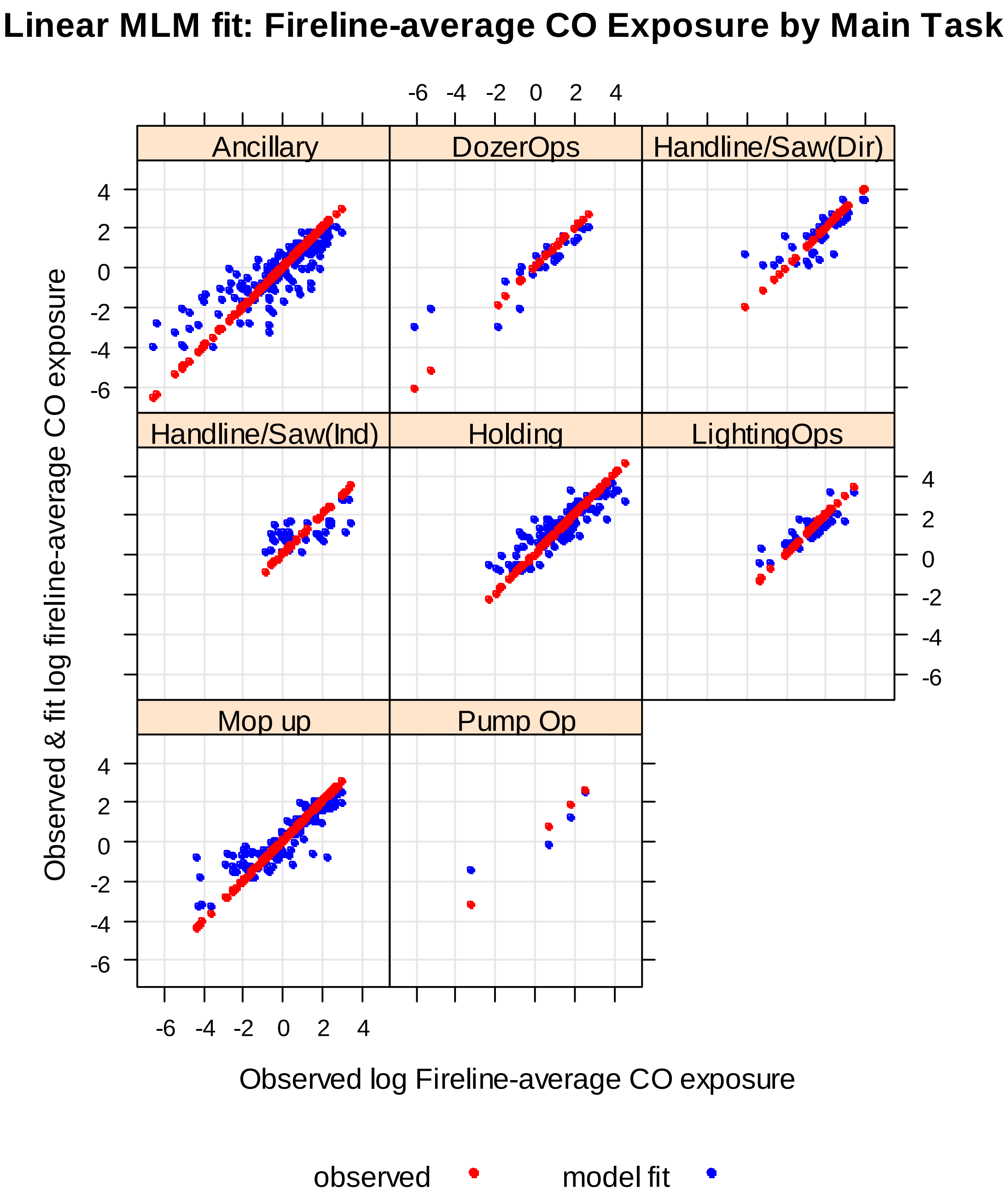


Figure 22. Modeled fireline-average carbon monoxide exposure by wind position

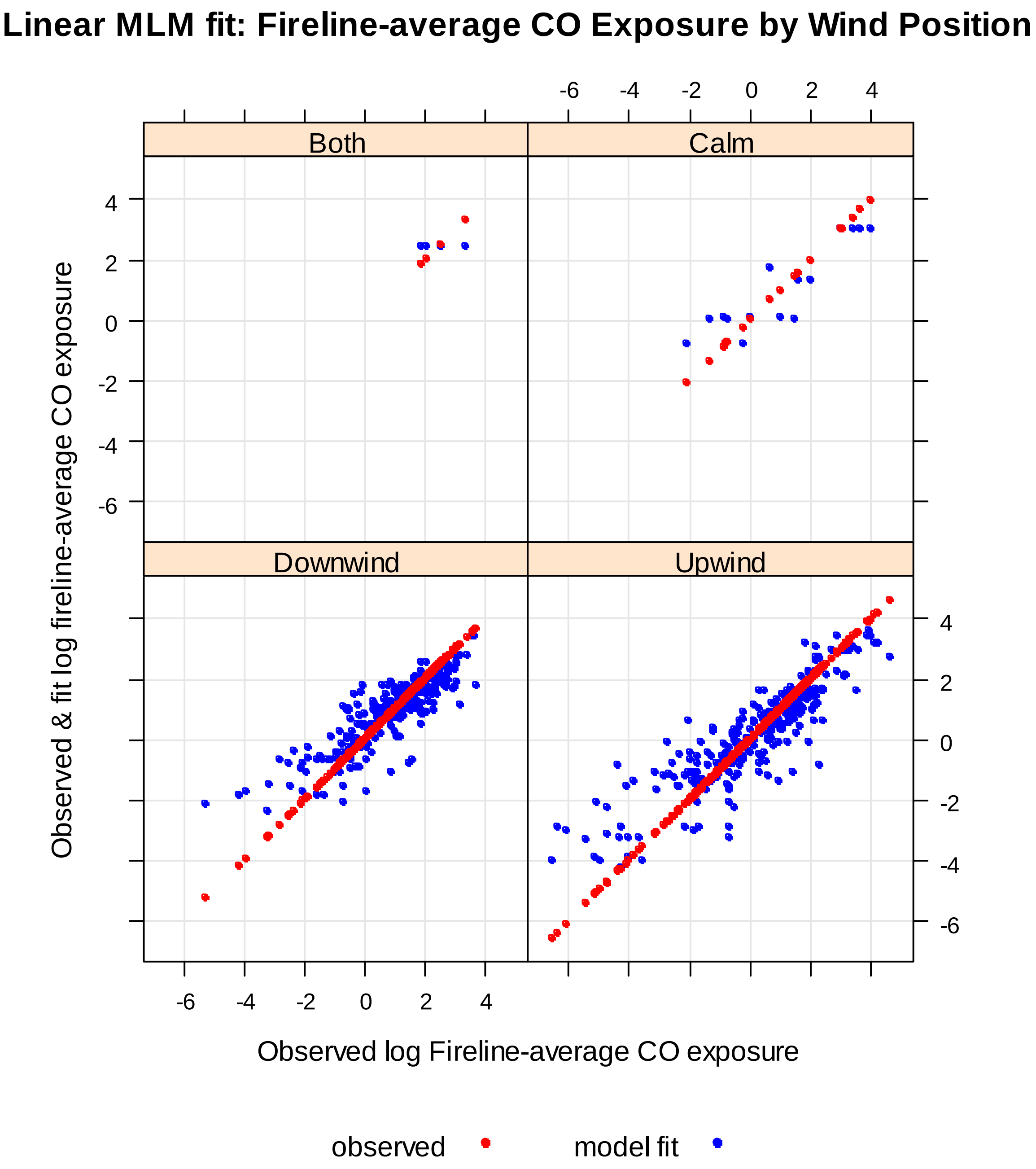


Figure 23. Modeled fireline-average carbon monoxide exposure by normalized main task time

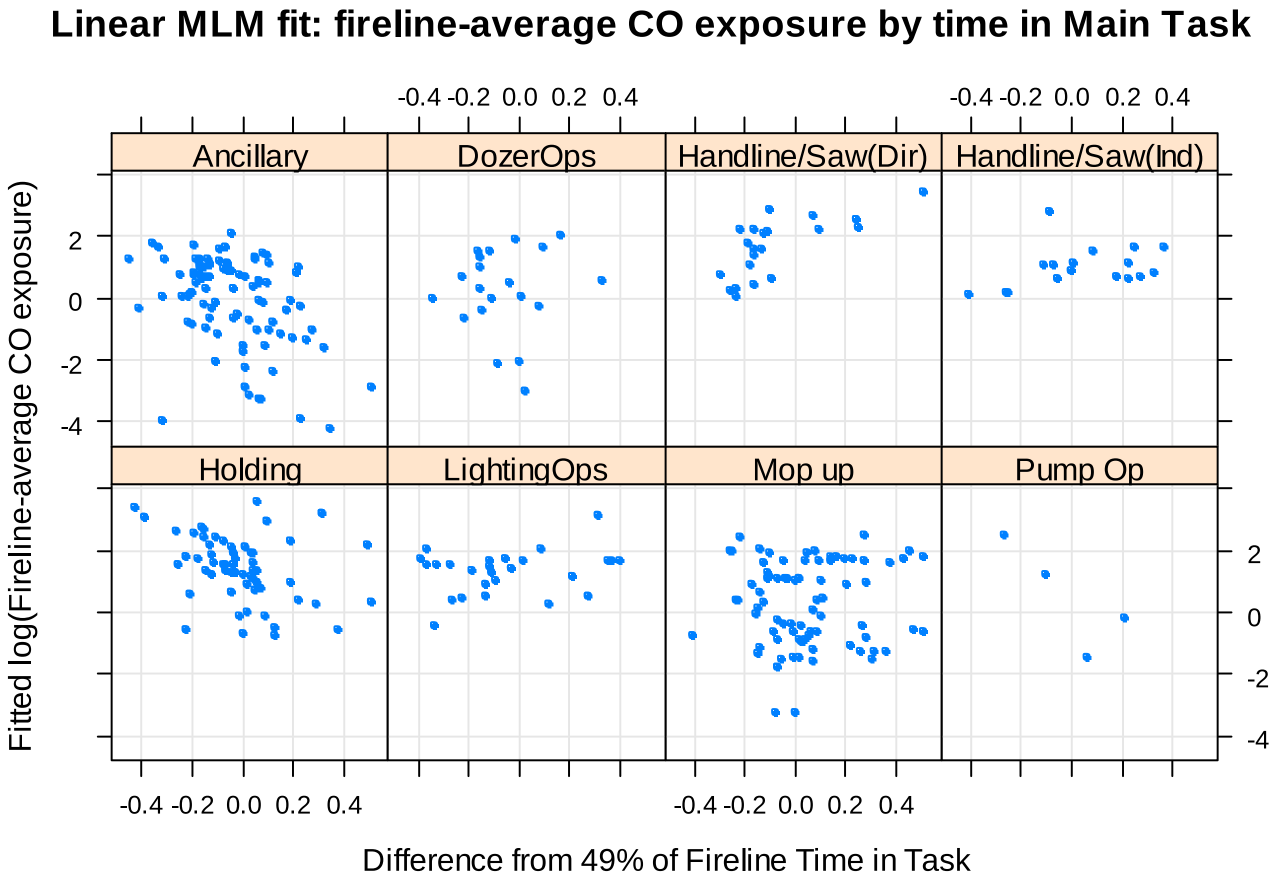


Figure 24. Modeled fireline-average carbon monoxide exposure by USFS region

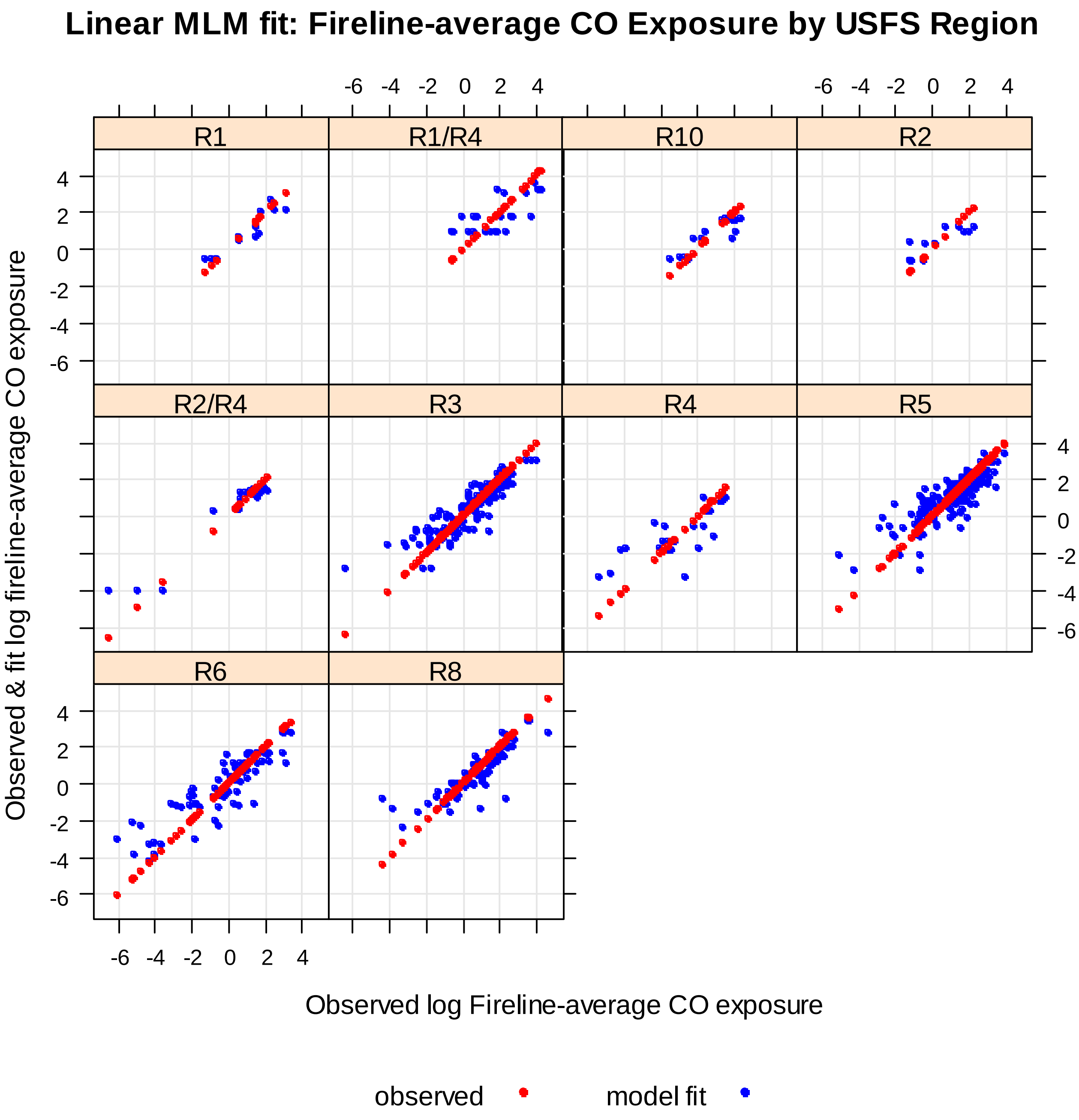


Figure 25. Contrast of fireline-average carbon monoxide exposure model means

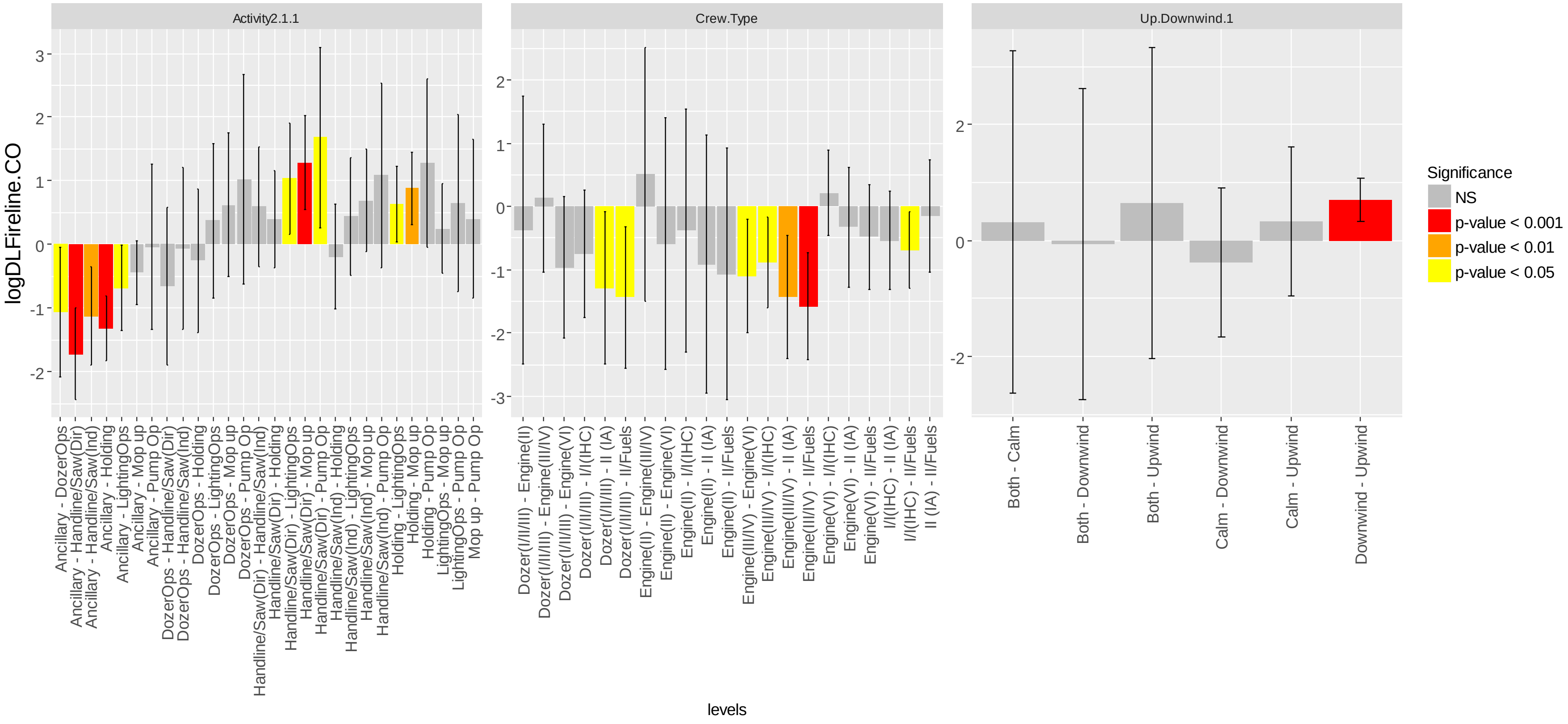


Figure 26. Modeled fireline-average respirable particulate exposure by crew type

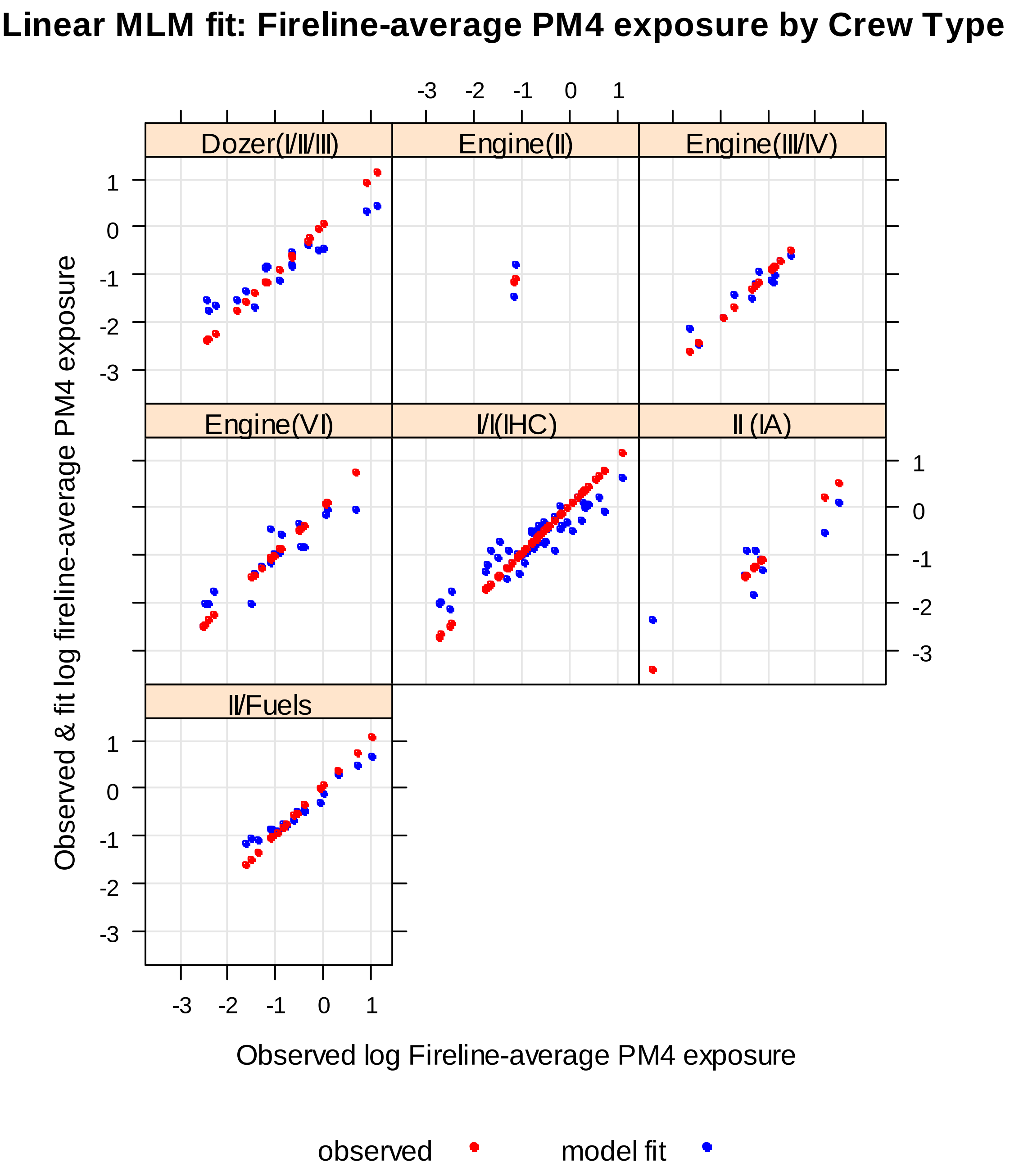


Figure 27. Modeled fireline-average respirable particulate matter exposure by fire type

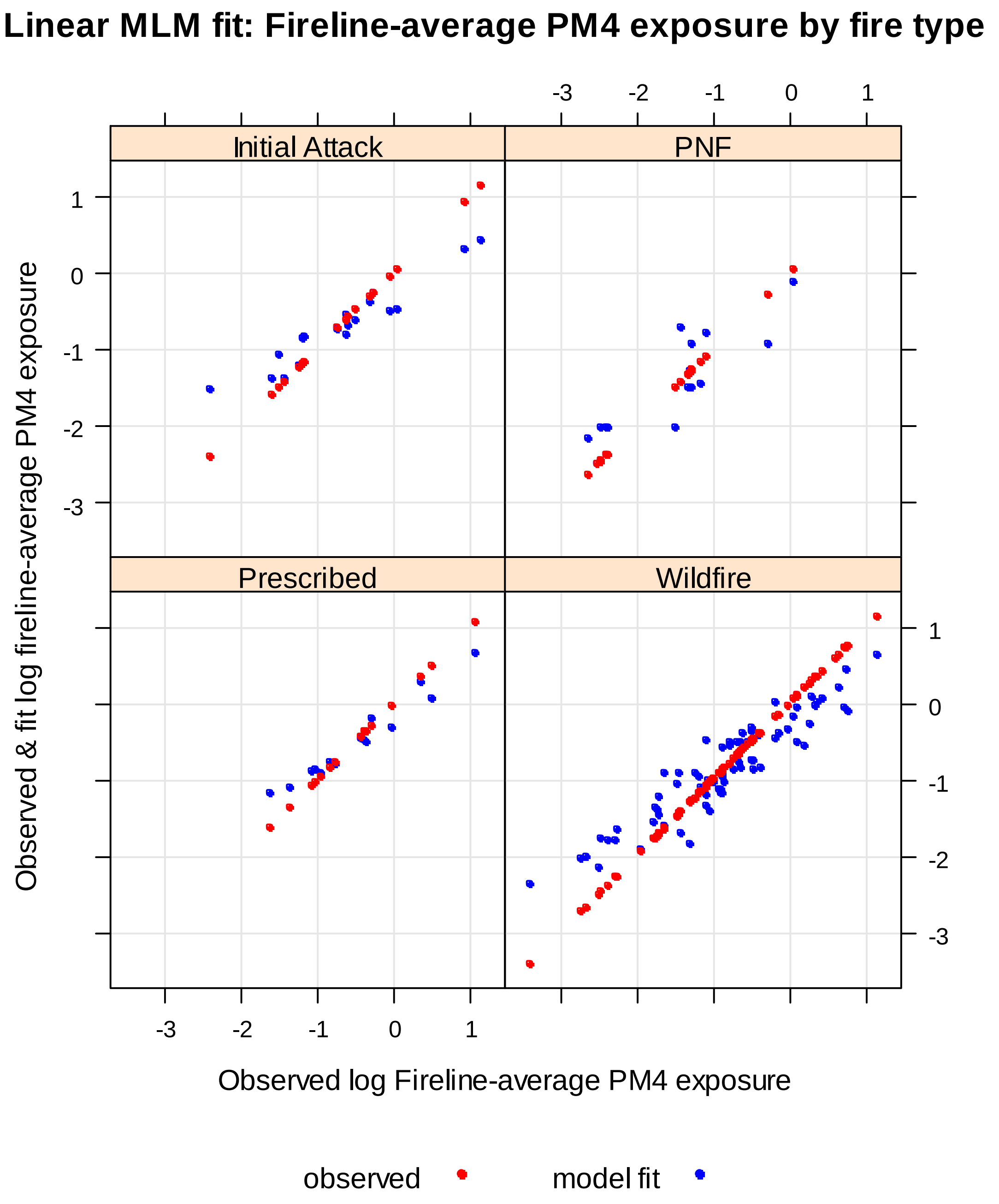


Figure 28. Modeled fireline-average respirable particulate exposure by main task

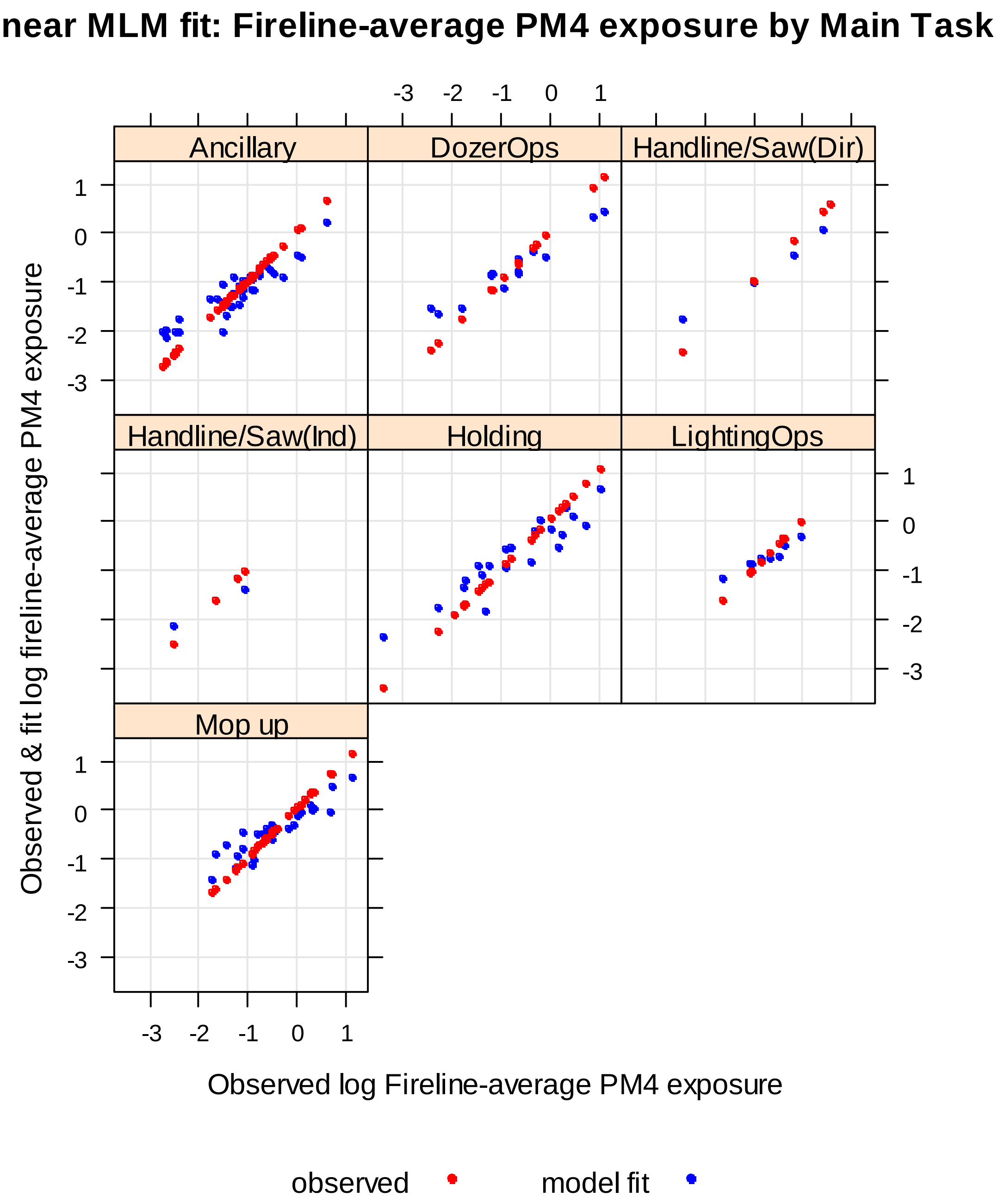


Figure 29. Modeled fireline-average respirable particulate exposure by Wind Position

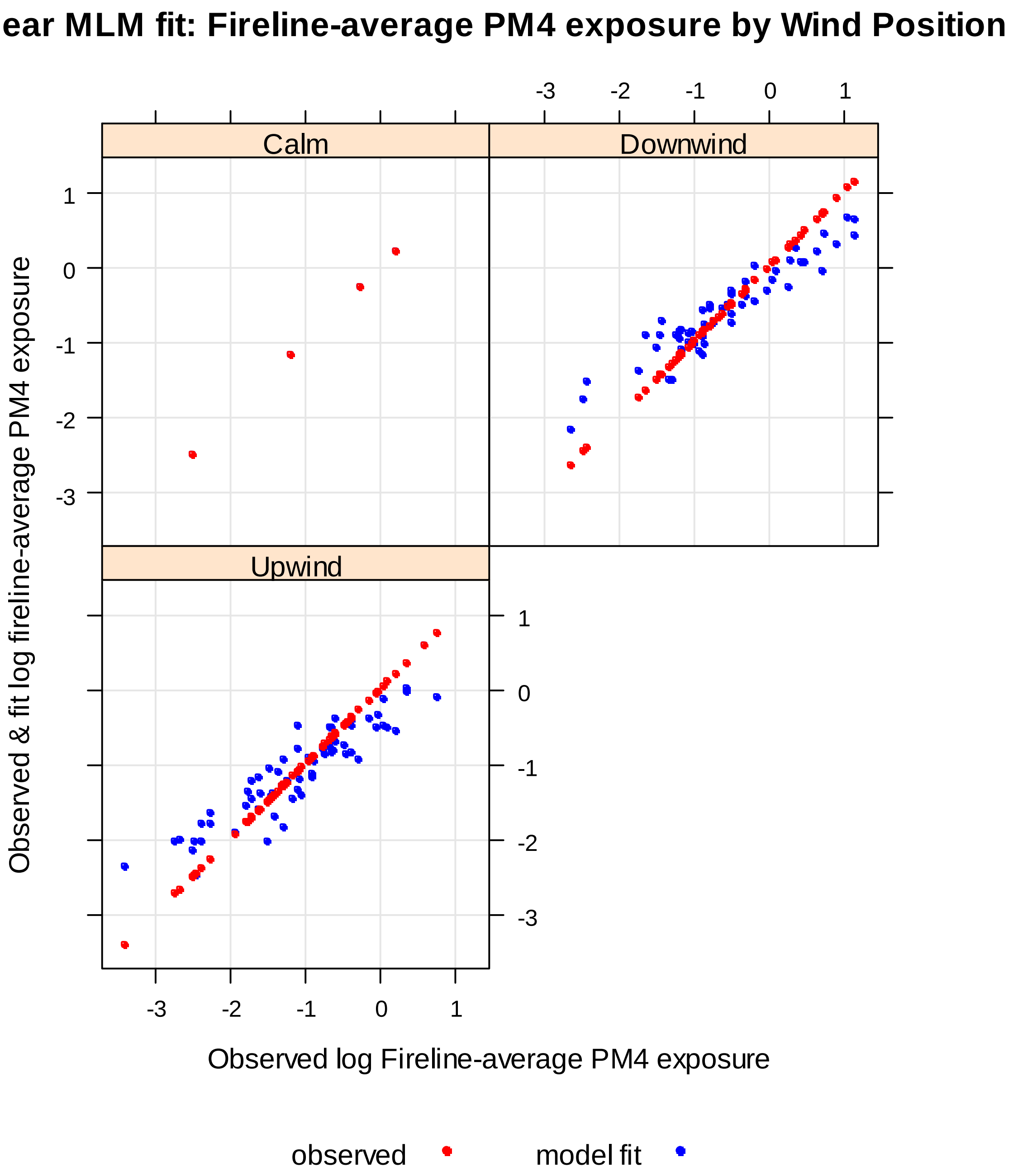


Figure 30. Modeled fireline-average respirable particulate exposure by normalized main task time

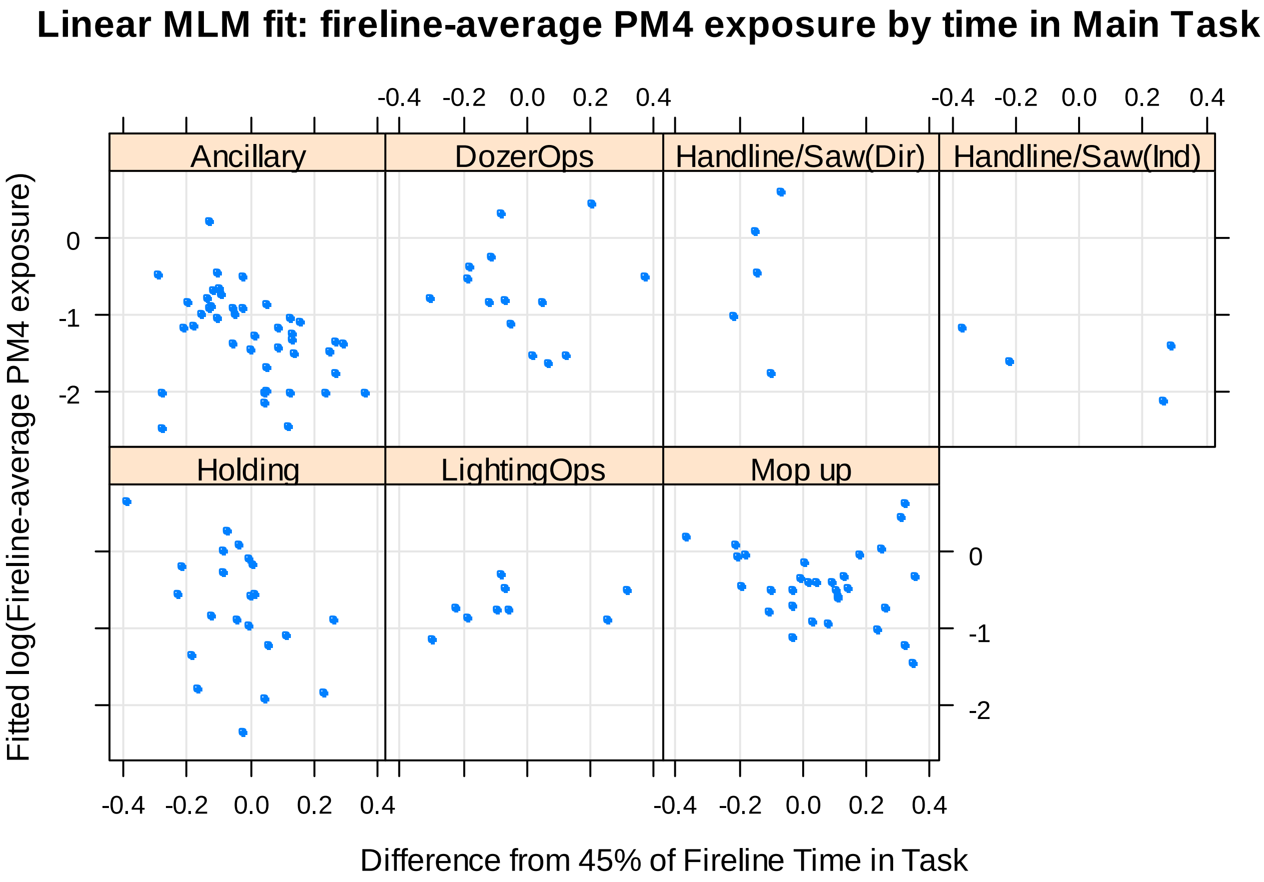


Figure 31. Modeled fireline-average respirable particulate exposure model fit by USFS region

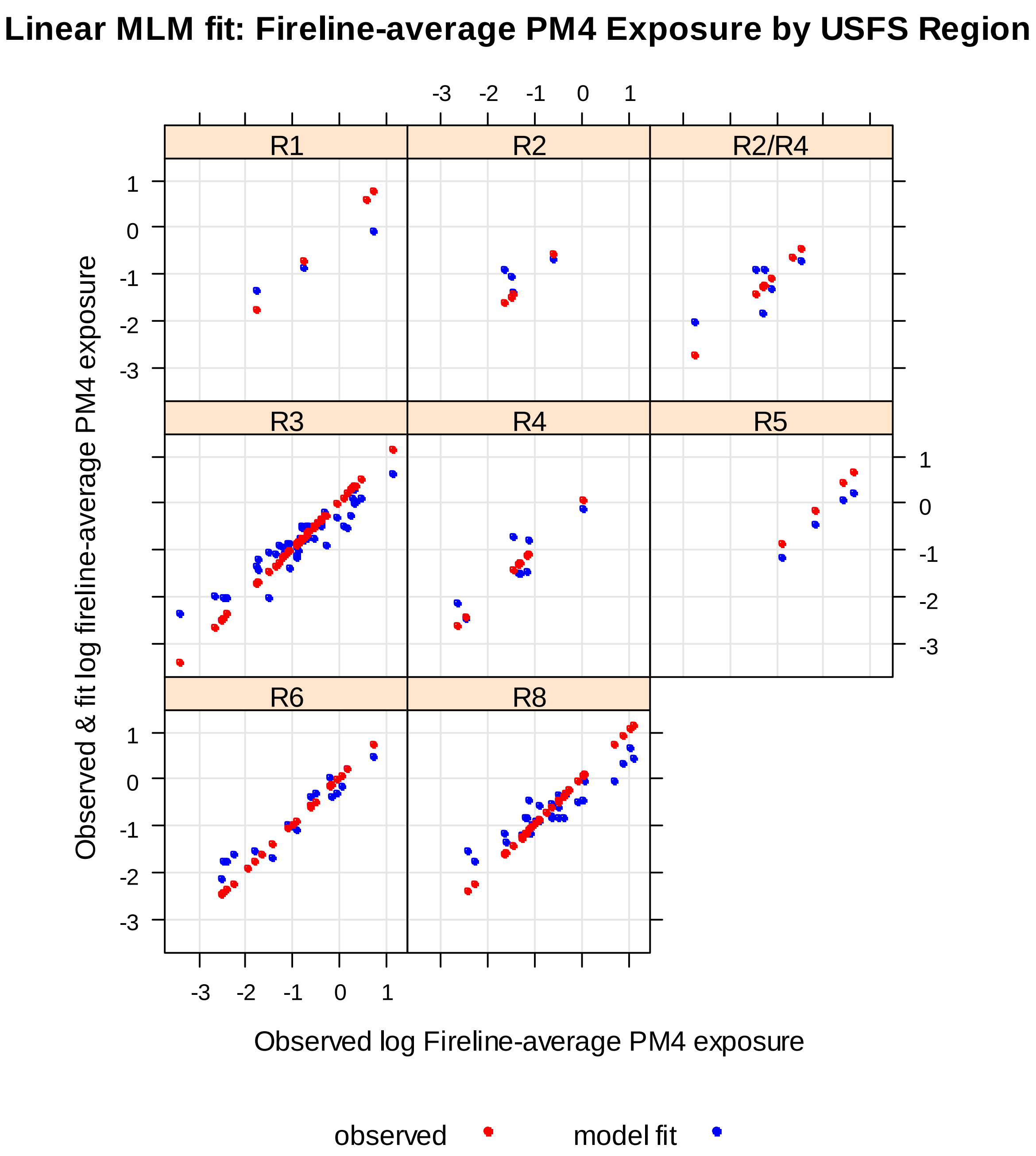


Figure 32. Contrast of fireline-average respirable particulate exposure model means

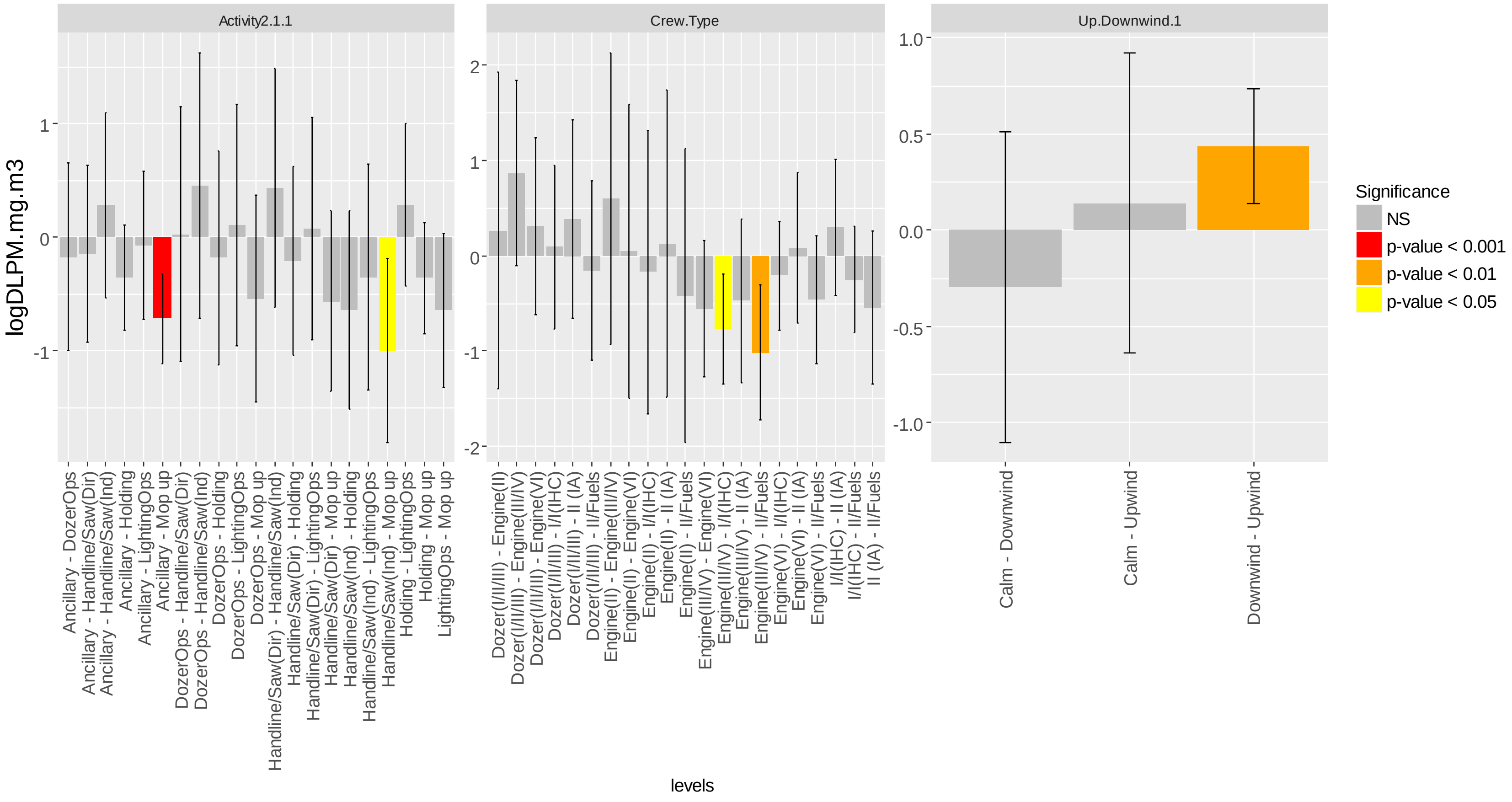


Figure 33. Modeled fireline-average respirable quartz exposure by Crew Type

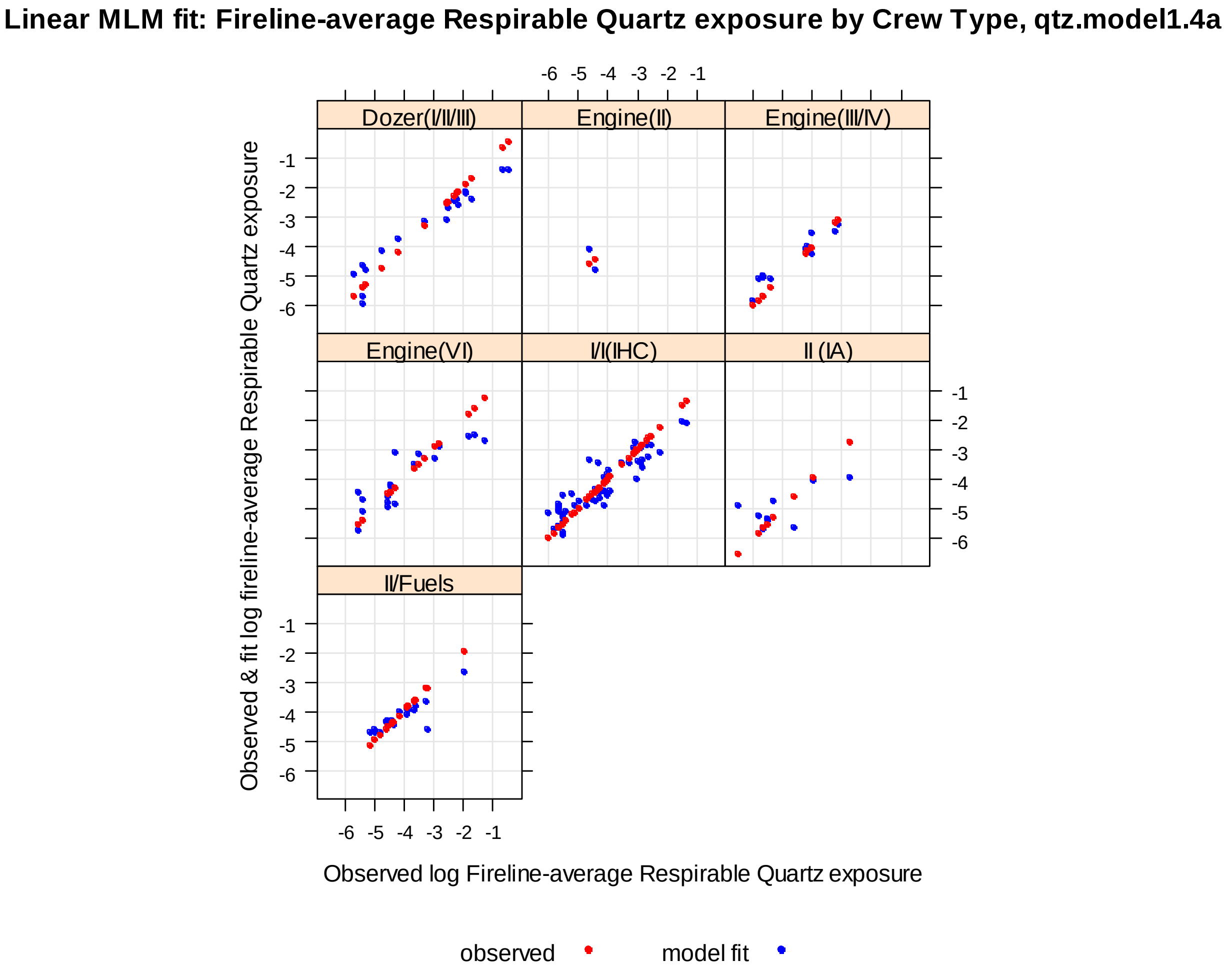


Figure 34. Modeled fireline-average respirable quartz exposure by Fire Type

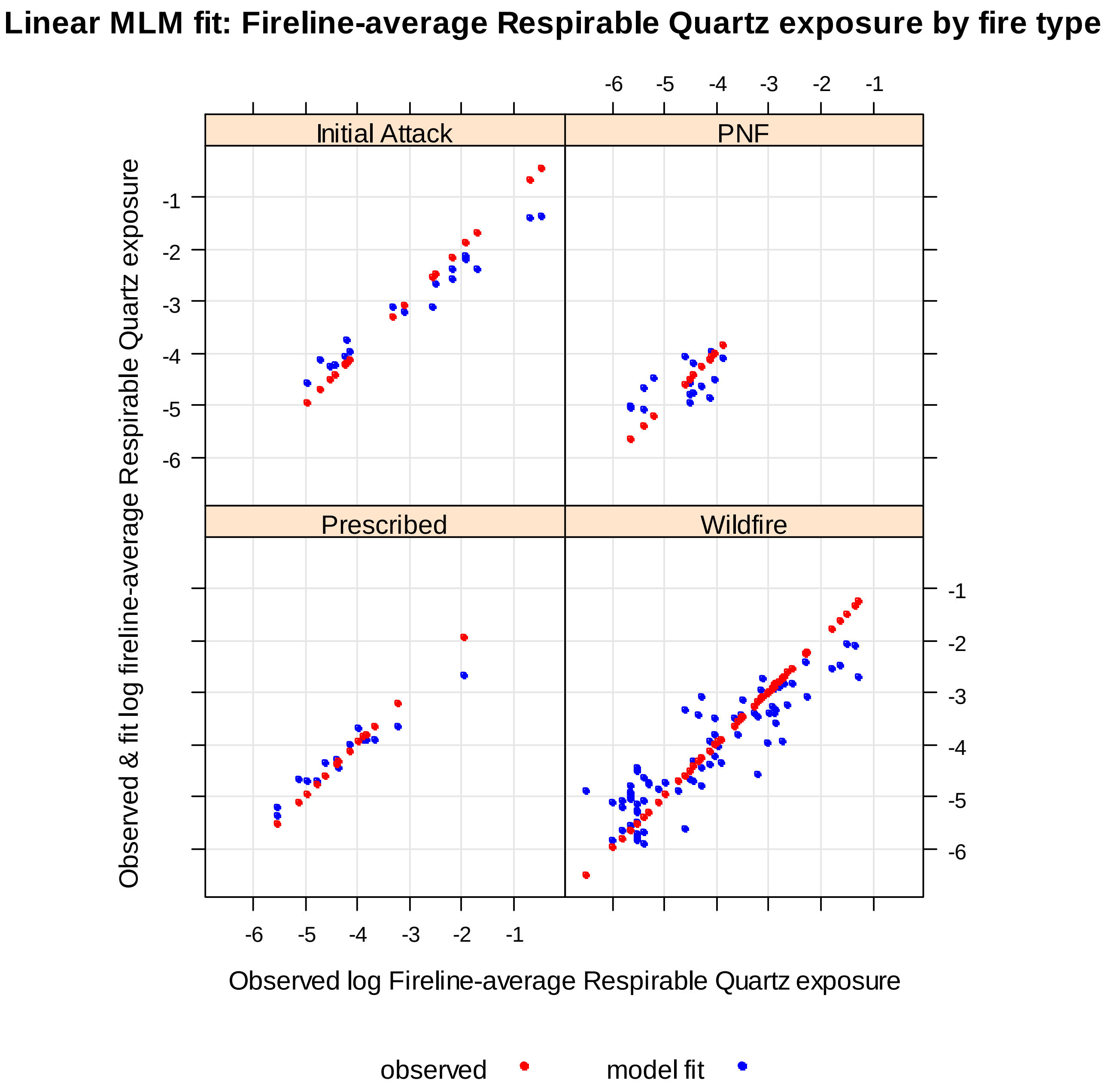
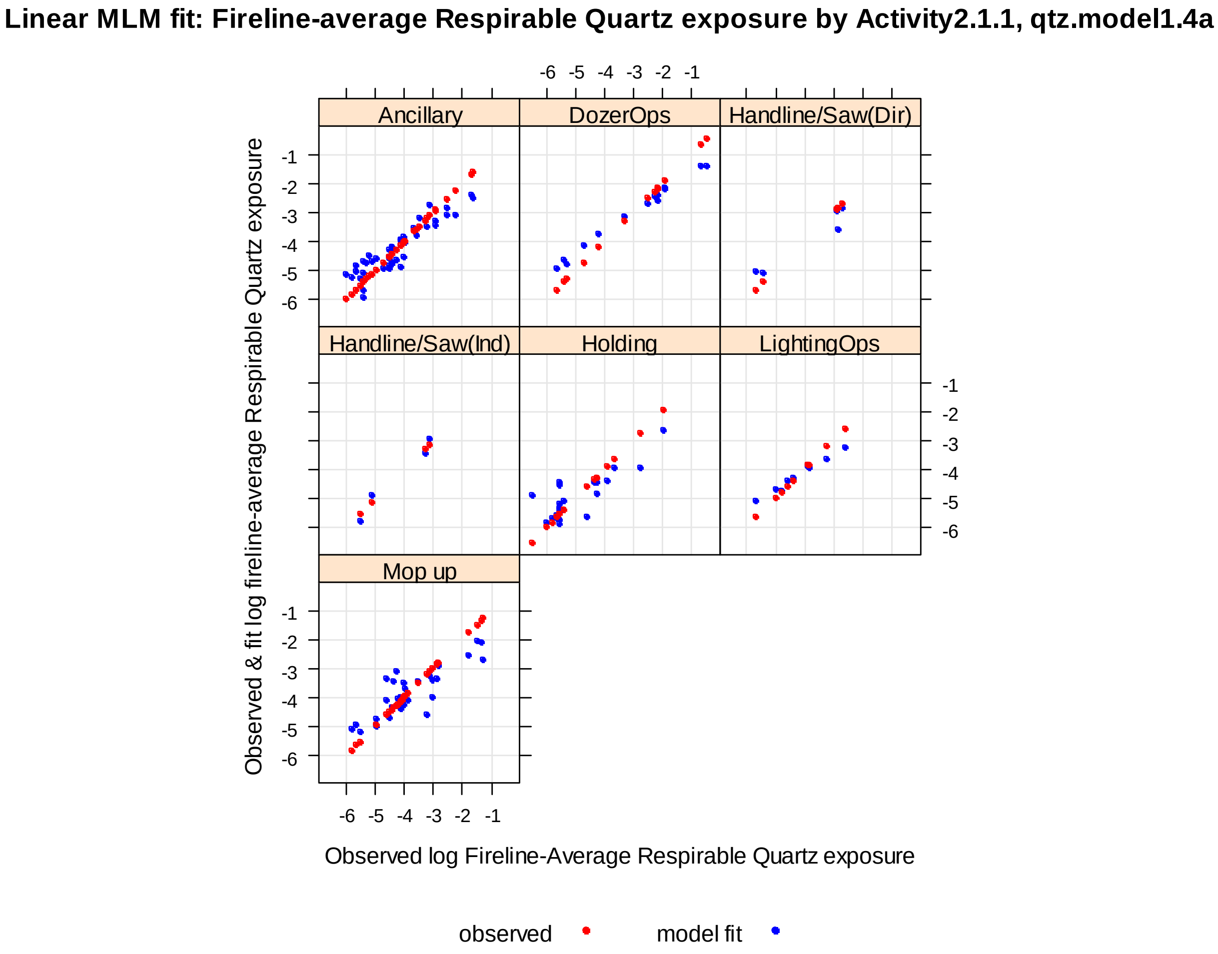


Figure 35. Modeled fireline-average respirable quartz exposure by Main Task



Linear MLM fit: Fireline-average Respirable Quartz exposure by Activity2.1.1, qtz.model1.4a

Figure 36. Modeled fireline-average respirable quartz exposure by wind position

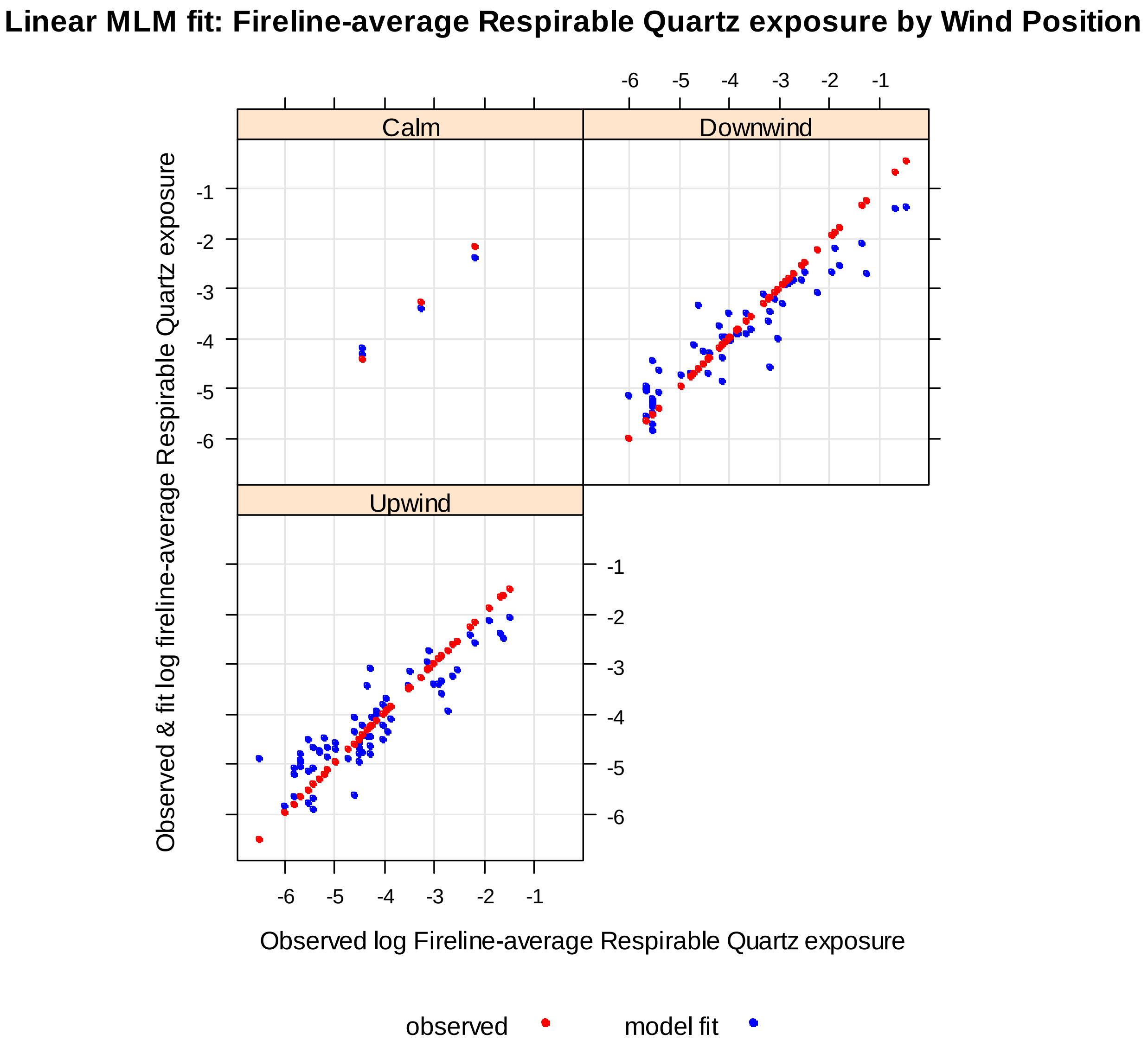


Figure 37. Modeled fireline-average respirable quartz exposure by normalized main task time

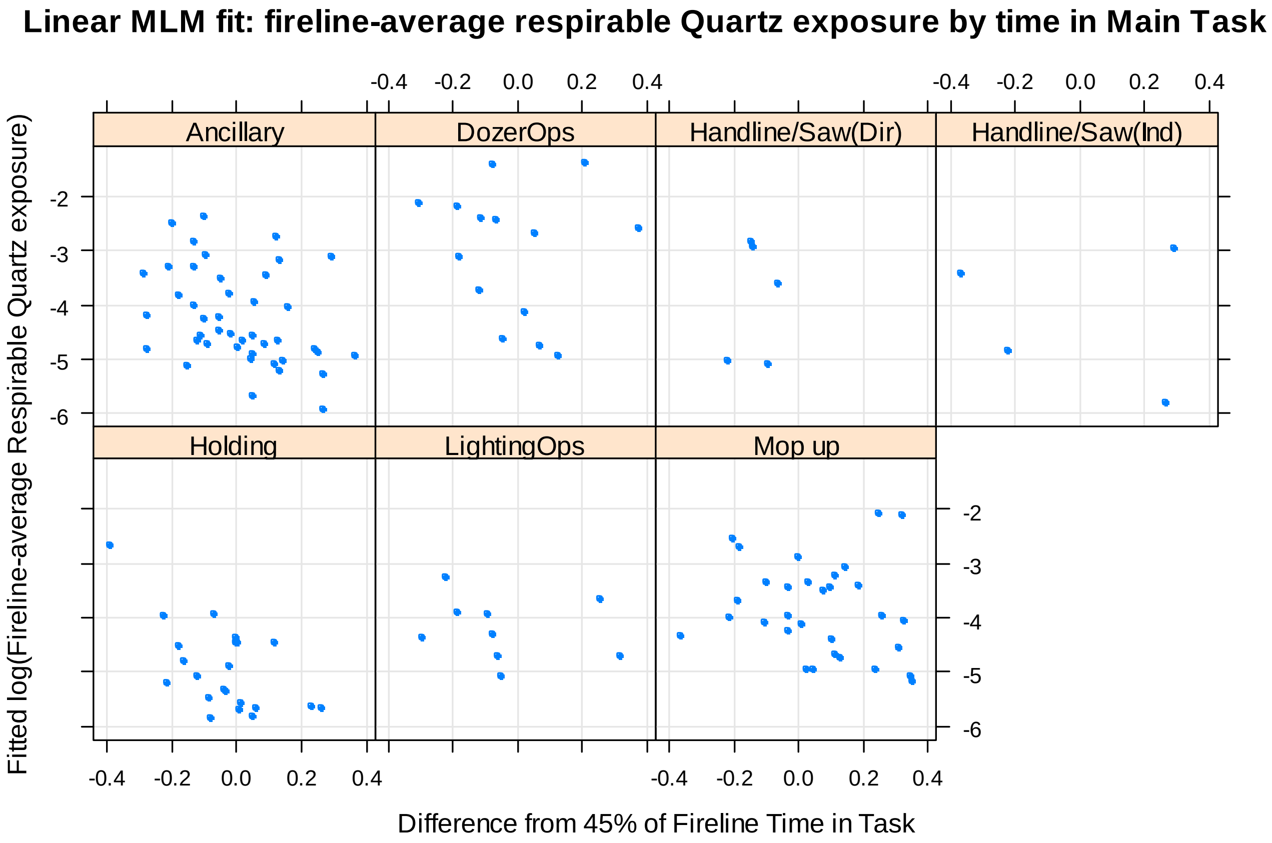


Figure 38. Modeled fireline-average respirable quartz exposure model fit by USFS region

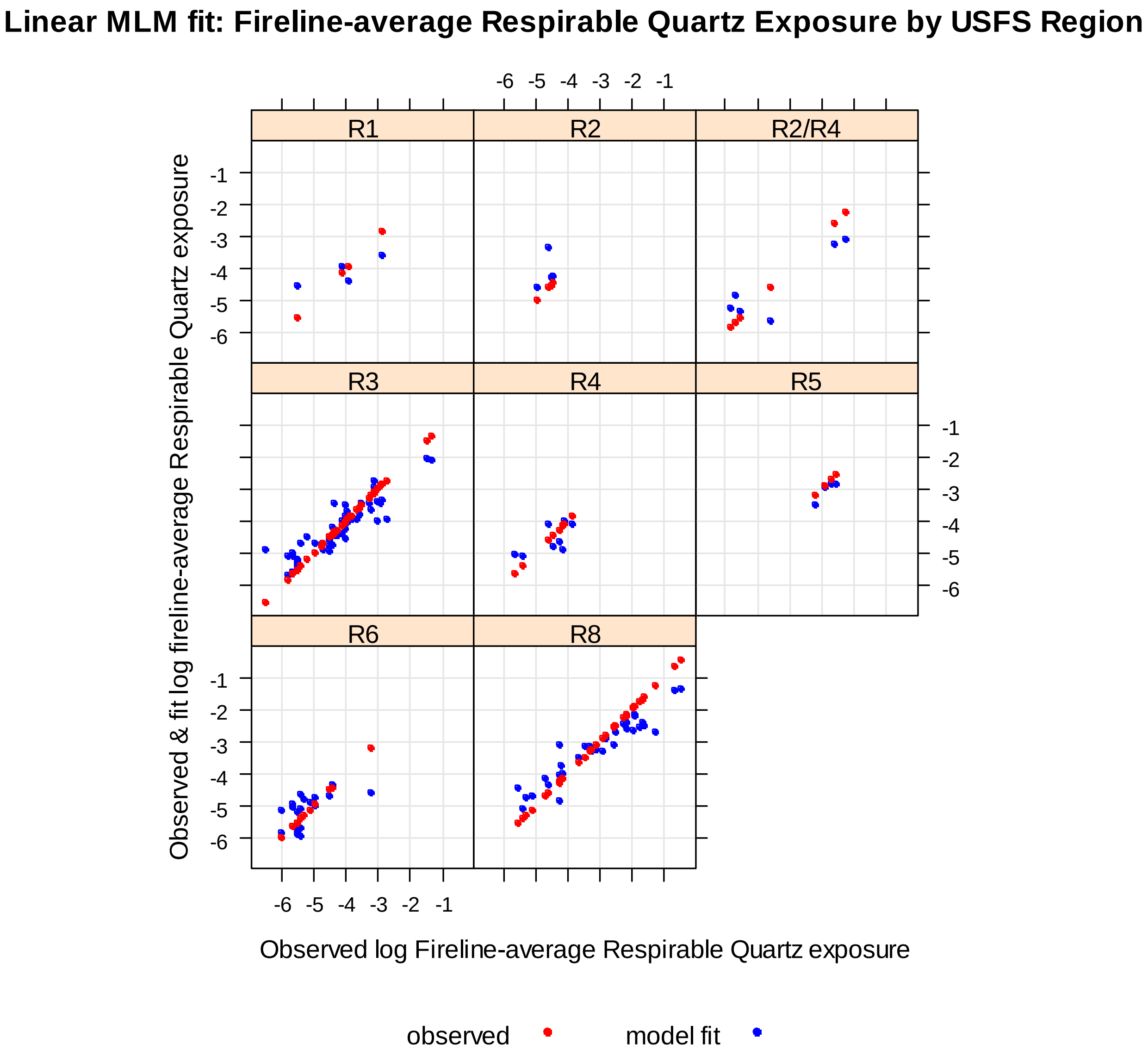


Figure 39. Contrast of fireline-average respirable quartz exposure model means

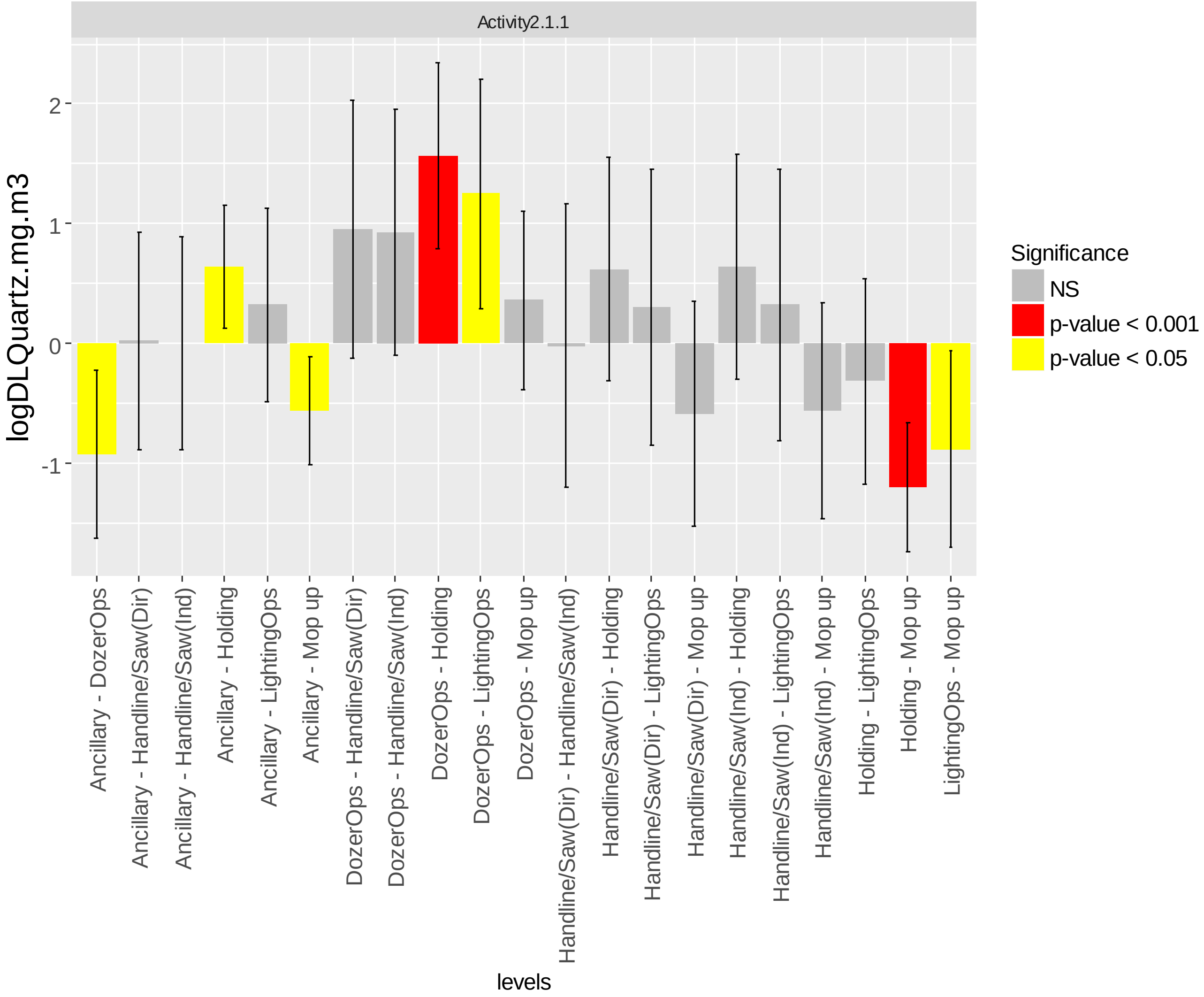


Figure 40. Correlation of respirable particulate & carbon monoxide exposures by work activity

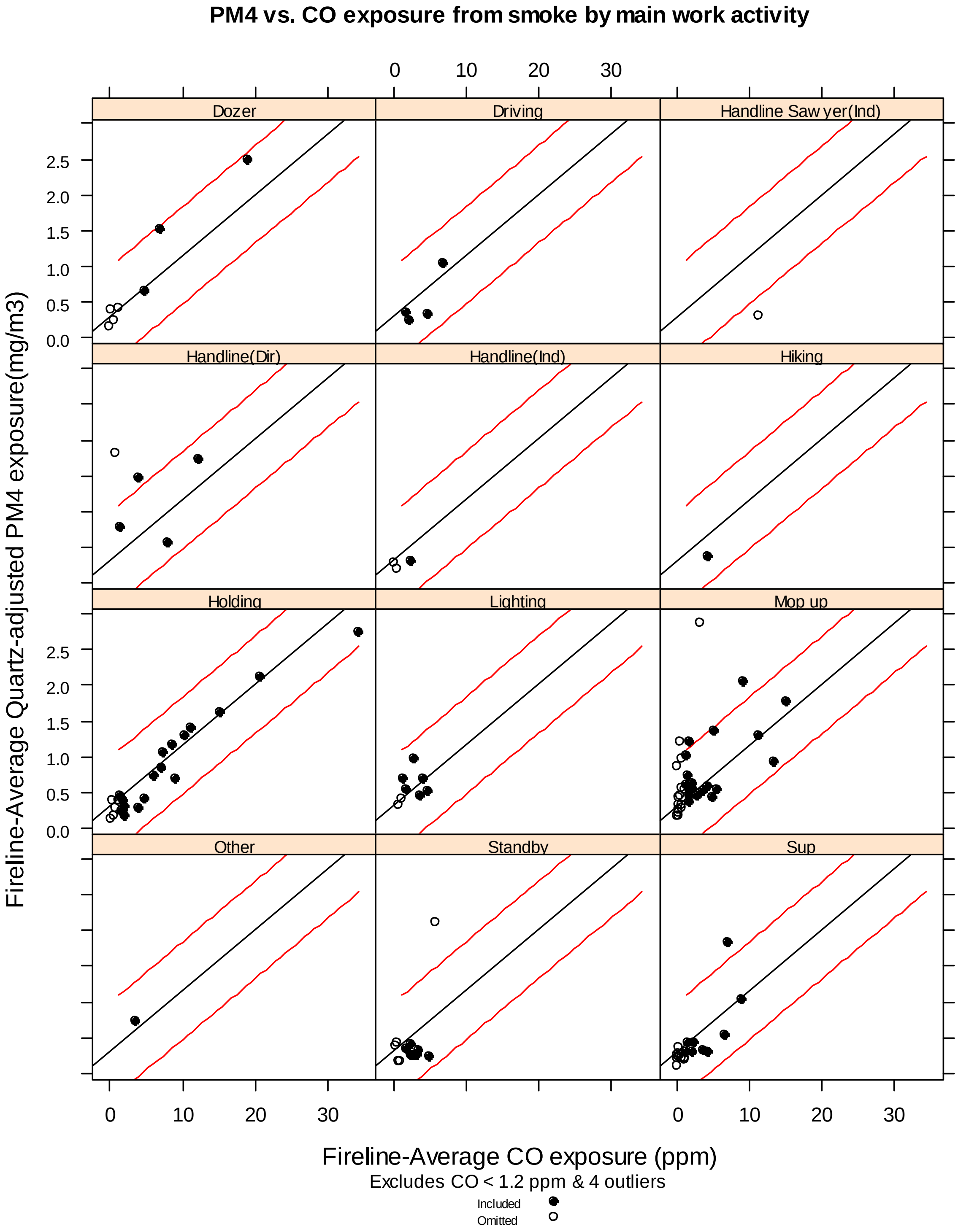
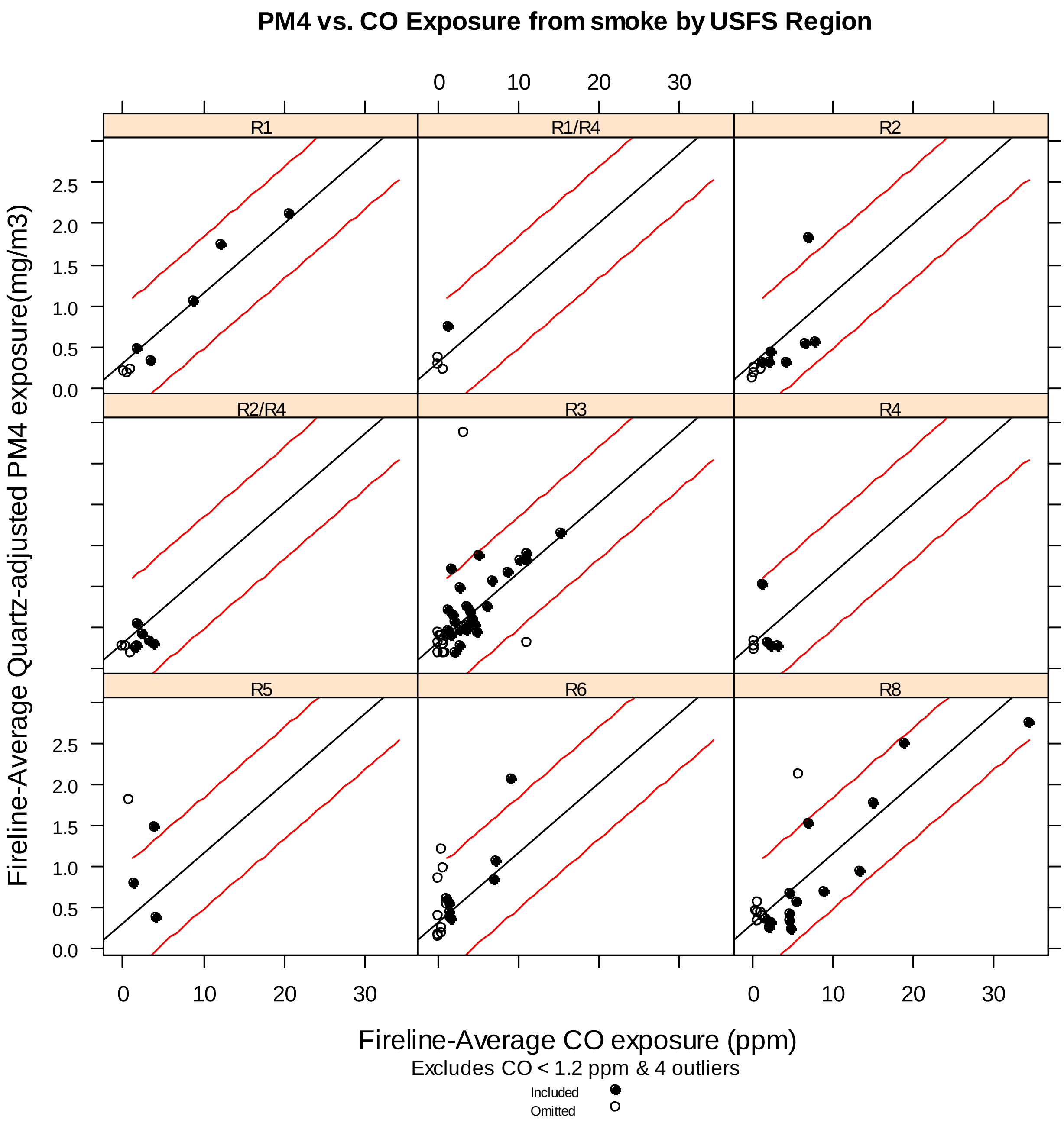


Figure 41. Correlation of respirable particulate & carbon monoxide exposures by USFS Region



Appendix A—Multilevel Model Output

Multilevel Model for 5-Minute STEL Exposure

```
> summary(co.stelmodel.6)
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: logDLMax.5.Min.CO ~ Crew.Type + X5.Min.Act2 * gCtr.Windspeed.5 +      (1 | daycrew)
   Data: stel.ffs

REML criterion at convergence: 1684.8

Scaled residuals: 
    Min      1Q  Median      3Q     Max 
-4.3282 -0.4080  0.0544  0.4859  2.5617 

Random effects:
 Groups   Name        Variance Std.Dev.
 daycrew  (Intercept) 0.8247   0.9081  
 Residual             0.5714   0.7559  
Number of obs: 585, groups:  daycrew, 207

Fixed effects:
                                               Estimate Std. Error        df t value Pr(>|t|)    
(Intercept)                                     1.92414    0.39335 422.90000   4.892 1.42e-06 ***
Crew.TypeEngine(II,III/IV)                     -0.01311    0.46882 355.00000  -0.028 0.977705    
Crew.TypeEngine(VI)                             0.79352    0.46602 353.50000   1.703 0.089492 .  
Crew.TypeI/I(IHC)                               0.94879    0.41125 413.60000   2.307 0.021545 *  
Crew.TypeII (IA)                                1.36297    0.48531 328.90000   2.808 0.005275 ** 
Crew.TypeII/Fuels                               1.27139    0.44424 375.60000   2.862 0.004446 ** 
X5.Min.Act2DozerOps                             1.16390    0.41442 555.30000   2.809 0.005152 ** 
X5.Min.Act2Handline/Saw(Dir)                    0.87882    0.17296 557.90000   5.081 5.13e-07 ***
X5.Min.Act2Handline/Saw(Ind)                    0.82835    0.21731 528.60000   3.812 0.000154 ***
X5.Min.Act2Holding                              0.64708    0.16916 561.50000   3.825 0.000145 ***
X5.Min.Act2LightingOps                          0.40781    0.20134 557.30000   2.025 0.043296 *  
X5.Min.Act2Mop up                               0.53023    0.15469 543.80000   3.428 0.000655 ***
X5.Min.Act2Pump Op                             -0.16461    0.49855 539.00000  -0.330 0.741394    
gCtr.Windspeed.5                               -0.03672    0.05858 548.80000  -0.627 0.531022    
X5.Min.Act2DozerOps:gCtr.Windspeed.5            0.51796    0.15102 488.00000   3.430 0.000655 ***
X5.Min.Act2Handline/Saw(Dir):gCtr.Windspeed.5   0.08640    0.08099 527.50000   1.067 0.286522    
X5.Min.Act2Handline/Saw(Ind):gCtr.Windspeed.5   0.13367    0.12143 530.90000   1.101 0.271483    
X5.Min.Act2Holding:gCtr.Windspeed.5             0.13217    0.07235 509.90000   1.827 0.068332 .  
X5.Min.Act2LightingOps:gCtr.Windspeed.5         0.16369    0.09351 561.80000   1.750 0.080584 .  
X5.Min.Act2Mop up:gCtr.Windspeed.5              0.03624    0.08242 534.20000   0.440 0.660377    
X5.Min.Act2Pump Op:gCtr.Windspeed.5             0.25210    0.22051 440.10000   1.143 0.253566    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Multilevel Model for Fireline-Average CO Exposure

```
> summary(co.model1.8c2)

Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: logDLFireline.CO ~ Crew.Type + Activity2.1.1 + gCtr.Pct.Fline.1 +      Up.Downwind.1 + (1 |
daycrew) + Activity2.1.1:gCtr.Pct.Fline.1
   Data: fline.facts

REML criterion at convergence: 2071.3

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.5325 -0.3940  0.0884  0.4931  3.1157

Random effects:
 Groups   Name        Variance Std.Dev.
 daycrew  (Intercept) 1.469    1.212
 Residual             1.009    1.004
Number of obs: 621, groups:  daycrew, 208

Fixed effects:
                                                 Estimate Std. Error        df t value Pr(>|t|)
(Intercept)                                      -0.53973    1.43670 187.60000  -0.376 0.707585
Crew.TypeEngine(II)                               0.37260    1.07691 214.80000   0.346 0.729691
Crew.TypeEngine(III/IV)                          -0.13794    0.59489 316.40000  -0.232 0.816788
Crew.TypeEngine(VI)                               0.96175    0.57250 329.40000   1.680 0.093921 .
Crew.TypeI/I(IHC)                                 0.74926    0.51074 384.10000   1.467 0.143190
Crew.TypeII (IA)                                  1.28665    0.61462 305.70000   2.093 0.037138 *
Crew.TypeII/Fuels                                 1.43947    0.57042 340.30000   2.524 0.012073 *
Activity2.1.1DozerOps                             1.06291    0.51579 584.90000   2.061 0.039768 *
Activity2.1.1Handline/Saw(Dir)                    1.71950    0.36563 352.70000   4.703 3.69e-06 ***
Activity2.1.1Handline/Saw(Ind)                    1.12556    0.39044 303.70000   2.883 0.004223 **
Activity2.1.1Holding                              1.31913    0.26045 280.00000   5.065 7.43e-07 ***
Activity2.1.1LightingOps                          0.68638    0.34102 363.20000   2.013 0.044881 *
Activity2.1.1Mop up                               0.43952    0.25593 290.40000   1.717 0.086984 .
Activity2.1.1Pump Op                              0.03770    0.66377 582.20000   0.057 0.954730
gCtr.Pct.Fline.1                                 -3.07653    0.83326 322.20000  -3.692 0.000261 ***
Up.Downwind.1Calm                                -0.31867    1.49260 172.90000  -0.214 0.831188
Up.Downwind.1Downwind                             0.06076    1.35939 171.50000   0.045 0.964403
Up.Downwind.1Upwind                              -0.64792    1.36034 171.90000  -0.476 0.634468
Activity2.1.1DozerOps:gCtr.Pct.Fline.1            3.66586    2.07174 494.60000   1.769 0.077434 .
Activity2.1.1Handline/Saw(Dir):gCtr.Pct.Fline.1   6.20419    1.71119 284.60000   3.626 0.000341 ***
Activity2.1.1Handline/Saw(Ind):gCtr.Pct.Fline.1   4.73624    1.85663 285.70000   2.551 0.011263 *
Activity2.1.1Holding:gCtr.Pct.Fline.1             1.52548    1.26094 344.70000   1.210 0.227185
Activity2.1.1LightingOps:gCtr.Pct.Fline.1         3.25104    1.42867 426.30000   2.276 0.023367 *
Activity2.1.1Mop up:gCtr.Pct.Fline.1              2.85735    1.18636 310.10000   2.408 0.016601 *
Activity2.1.1Pump Op:gCtr.Pct.Fline.1            -0.37171    3.67497 576.10000  -0.101 0.919469
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Multilevel Model for Fireline-Average PM4 Exposure

```
> summary(pm4.model1.8a)
Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: logDLPM.mg.m3 ~ Activity2.1.1 + Up.Downwind.1 + Crew.Type + (1 |      Fire.Name2/Crew.Name)
   Data: fline.facts.pm

REML criterion at convergence: 302.4

Scaled residuals:
     Min       1Q   Median       3Q      Max 
-2.01294 -0.43469  0.02972  0.42095  1.40013 

Random effects:
 Groups               Name        Variance Std.Dev.
 Crew.Name:Fire.Name2 (Intercept) 0.32492  0.5700  
 Fire.Name2           (Intercept) 0.06597  0.2568  
 Residual                         0.30799  0.5550  
Number of obs: 128, groups:  Crew.Name:Fire.Name2, 104; Fire.Name2, 50

Fixed effects:
                                Estimate Std. Error        df t value Pr(>|t|)    
(Intercept)                     -0.94469    0.54240  79.18000  -1.742 0.085450 .  
Activity2.1.1DozerOps            0.17521    0.41312  57.82000   0.424 0.673059    
Activity2.1.1Handline/Saw(Dir)   0.14928    0.39270 103.42000   0.380 0.704623    
Activity2.1.1Handline/Saw(Ind)  -0.28117    0.40694  63.35000  -0.691 0.492134    
Activity2.1.1Holding             0.35782    0.23413 103.90000   1.528 0.129469    
Activity2.1.1LightingOps         0.07053    0.32999  99.58000   0.214 0.831200    
Activity2.1.1Mop up              0.71625    0.19940 100.77000   3.592 0.000509 ***
Up.Downwind.1Downwind            0.29464    0.40667  81.65000   0.725 0.470807    
Up.Downwind.1Upwind             -0.14183    0.39228  75.63000  -0.362 0.718689    
Crew.TypeEngine(II)             -0.26345    0.82922  70.15000  -0.318 0.751652    
Crew.TypeEngine(III/IV)         -0.85913    0.48950 105.90000  -1.755 0.082128 .  
Crew.TypeEngine(VI)             -0.30480    0.46609  85.07000  -0.654 0.514901    
Crew.TypeI/I(IHC)               -0.09351    0.43166  90.63000  -0.217 0.828975    
Crew.TypeII (IA)                -0.38599    0.52294 100.50000  -0.738 0.462158    
Crew.TypeII/Fuels                0.15673    0.47383 100.66000   0.331 0.741505    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Multilevel Model for Fireline-Average Respirable Crystalline Silica Exposure

```
> summary(qtz.model1.4a)

Linear mixed model fit by REML
t-tests use  Satterthwaite approximations to degrees of freedom ['lmerMod']
Formula: logDLQuartz.mg.m3 ~ Activity2.1.1 + gCtr.Pct.Fline.1 + (1 | Fire.Name2/Crew.Name)
   Data: fline.facts.pm

REML criterion at convergence: 365.1

Scaled residuals:
     Min       1Q   Median       3Q      Max
-2.23077 -0.43554  0.01759  0.42899  2.00195

Random effects:
 Groups               Name        Variance Std.Dev.
 Crew.Name:Fire.Name2 (Intercept) 0.1276   0.3573
 Fire.Name2           (Intercept) 0.9063   0.9520
 Residual                         0.5200   0.7211
Number of obs: 128, groups:  Crew.Name:Fire.Name2, 104; Fire.Name2, 50

Fixed effects:
                                 Estimate Std. Error         df t value Pr(>|t|)
(Intercept)                    -3.913e+00  2.150e-01  7.878e+01 -18.201   <2e-16 ***
Activity2.1.1DozerOps           9.259e-01  3.542e-01  9.677e+01   2.614   0.0104 *
Activity2.1.1Handline/Saw(Dir) -2.287e-02  4.573e-01  9.050e+01  -0.050   0.9602
Activity2.1.1Handline/Saw(Ind) -8.450e-06  4.451e-01  7.674e+01   0.000   1.0000
Activity2.1.1Holding           -6.408e-01  2.581e-01  8.124e+01  -2.483   0.0151 *
Activity2.1.1LightingOps       -3.216e-01  4.068e-01  1.002e+02  -0.791   0.4311
Activity2.1.1Mop up             5.634e-01  2.294e-01  9.575e+01   2.456   0.0159 *
gCtr.Pct.Fline.1               -1.168e+00  5.087e-01  1.012e+02  -2.296   0.0238 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```