Uncontrolled Combustion of Shredded Tires in a Landfill

Part 2: Population Exposure, Public Health Response, and an Air Quality Index for Urban Fires

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ABSTRACT:

The Iowa City Landfill in eastern Iowa, United States, experienced a fire lasting 18 days in 2012, in which a drainage layer of over 1 million shredded tires burned, generating smoke that impacted the surrounding metropolitan area of 130,000 people. This emergency required air monitoring, risk assessment, dispersion modeling, and public notification. This paper quantifies the impact of the fire on local air quality and proposes a monitoring approach and an Air Quality Index (AQI) for use in future tire fires and other urban fires. Individual fire pollutants are ranked for acute and cancer relative risks using hazard ratios, with the highest acute hazard ratios attributed to SO_2, particulate matter, and aldehydes. Using a dispersion model in conjunction with the new AQI, we estimate that smoke concentrations reached unhealthy outdoor levels for sensitive groups out to distances of 3.1 km and 18 km at 24-h and 1-h average times, respectively. Modeled and measured concentrations of $PM_{2.5}$ from smoke and other compounds such as VOCs and benzo[a]pyrene are presented at a range of distances and averaging times, and the corresponding cancer risks are discussed. Through reflection on the air quality response to the event, consideration of cancer and acute risks, and comparison to other tire fires, we recommend that all landfills with shredded tire liners plan for hazmat fire emergencies. A companion paper presents emission factors and detailed smoke characterization.

Keywords: air quality index -; tire fire; Iowa City; hazard ratio

1. INTRODUCTION

Shredded tire chips are commonly used as landfill drainage lining material. They are permeable to leachate and protect the landfill liner (Cecich et al., 1996; FEMA/USFA, 2002; Fiksel et al., 2011; IWMB, 2002; Warith and Rao, 2006). This practice also offers a way to dispose of scrap tires (FEMA/USFA, 2002). However, shredded and whole tires pose a significant fire risk; they are difficult to extinguish once ignited and emit criteria pollutants and air toxics when combusted (Lemieux et al., 2004; Lemieux and Ryan, 1993; USFA, 1998; Wang et al., 2007).

The Iowa City landfill's shredded tire drainage layer was accidentally ignited and burned openly for 18 days beginning May 26, 2012 (Figure 1). The exposed shredded tire drainage layer was 1-m thick and covered 30,000 m^2 and the fire consumed an estimated 1.3 million tires (20,540 metric tons, assuming 15.8 kg $tire^{-1}$; RMA 2013). The Iowa City landfill was close enough to population centers of Johnson County, Iowa (population 152,586, U.S. 2010 Census) to impact people through smoke exposure, including densely populated neighborhoods.

Over a dozen major tire fires have occurred in the United States and Canada since 1983 (see CalEPA, 2002; DEQ, 1989, USFA, 1998; EPA 1997; Ritter, 2013). The Iowa City landfill fire was approximately five times smaller than the largest U.S. tire fire, the 1983 Rhinehart fire (Ritter, 2013). These types of fires often exceed one month in duration and pose threats to the health and safety of both firefighters and the public. In some cases, fires have prompted voluntary evacuations, school closings, and increased respiratory complaints. On occasion, tire fires have been documented through published air concentration measurements from environmental agencies (CalEPA, 2002; EPA, 1997; OMOE, 1990; Sidhu et al., 2006; USFA, 1998). Sampling results for polycyclic aromatic hydrocarbons (PAH) and metal residues on vegetation are also reported (CalEPA, 2002; Steer et al., 1995), as well as cancer risk assessment conducted using B[a]P concentrations (Sidhu, et al., 2006). While the Iowa City fire shares many similarities to the listed tire fires, it is, to our knowledge, the first major U.S. tire fire occurring in a landfill liner system instead of at a tire stockpile location.

From public health and air quality perspectives, the response to a large scale tire fire includes many decisions – what compounds to monitor; where to locate air monitors; whether to use mobile or fixed samplers; whether to use integrating or continuous techniques; interpretation of multi-pollutant mixture results across varied averaging times; action levels for warnings, evacuations, and closures; wording of public notices; recommended actions for reducing exposure; and best practices for using dispersion modeling.

Existing reports from past fires have major shortcomings as a guide to the public health response (JCPHD, 2012, Downard et al., co-submitted). Shortcomings include a lack of prioritization on what to measure and where to measure it, and a focus on reporting concentrations with limited interpretation of the public health impact. Past ambient studies rarely incorporate correction for dilution levels – limiting ability to generalize from measurements. Finally, variety in analyte selection and monitoring protocol is a challenge, with the monitoring focus varying among PAH, volatile organic compounds (VOCs), fine particulate matter ($PM_{2.5}$), and CO (CalEPA, 2002).

During the Iowa City incident, the public health response was led by the Johnson County Department of Public Health (JCPH) supported by State Hygienic Lab (SHL), the Iowa Department of Natural Resources (IDNR), EPA Region 7, and the University of Iowa. The combined measurement of various pollutants (see Downard et al., co submitted) and modeling work by these organizations enabled retrospective characterization of ambient concentrations.

This paper attempts to improve on the air quality response through a hierarchy of monitoring priorities for large scale tire fires, a tire fire irritant Air Quality Index (AQI) for interpretation of the measured values, and a ranking of tire fire components by acute and cancer hazard ratios. We also examine public health response guidelines and estimate emissions of some compounds not yet sampled in tire burning by using emissions profiles from open burning of oil (Booher, 1997; Lemieux, 2004). This work focuses on ambient air pollutants, and does not deal with the many other aspects of the emergency response.

2. Methods

2.1 Monitoring Sites and Instrumentation

Ambient air, often impacted with smoke, was examined at a variety of sites as mapped in Figure 2. Detailed descriptions of methods and instrumentation used to measure CO_2, CO, SO_2, particle number, $PM_{2.5}$, PM_{10}, PAH, and trace metals are in Downard et al. (co-submitted). Only additional measurements and site descriptions, as related to dispersion modeling and public health response, are described here. Additional information on detailed site locations, instruments deployed, and laboratory methodologies are located in Supplementary materials.

Ambient VOC concentrations were determined by EPA methods TO-12 and TO-15 (EPA, 1999). Ten grab samples, representing background and plume-impacted air, were collected in pre-cleaned 6-L Summa canisters (Entech Silonite™). Analysis was by gas chromatography (GC) mass spectrometry (Agilent Technologies 7890A, 5975C; 60 m DB-1 column).

Two stationary sites were critical to monitoring. Hoover Elementary School (EPA site ID 191032001) is located 10.5 km east of the Iowa City landfill in a residential area. This station monitors for 24-h average and hourly $PM_{2.5}$ using a low volume FRM sequential air sampler (R&P Model 2025 w/VSCC gravimetric) and a beta attenuation sampler (Met One BAM-1020 w/SCC beta attenuation), respectively. The University of Iowa Air Monitoring Site (IA-AMS) is located 4.2 km northeast of the landfill and is situated among recreational fields, low use parking areas, and woodlands.

2.2 Hazard ratios for tire fire smoke

Hazard ratios compare the ambient concentrations of pollutants to reference concentrations for a similar averaging period (EPA, 1989). The hazard ratio concept can be used to target specific pollutants in an exposure situation (Austin, 2008; EPA, 1989; McKenzie et al., 2012; Silverman et al., 2007). The hazard ratio (HR_i) for species *i* is

$$HR_i = \frac{c_i}{c_{ref}} \qquad (1)$$

where c_i is the ambient concentration and c_{ref} is the reference concentration. For the acute hazard ratio (HRA) we adopt 1-h Acute Exposure Guideline Levels (AEGL-1) (NRC, 2001) for c_{ref}. AEGL-1 is defined as "the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic nonsensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.” AEGL values were selected because they were developed specifically for emergency exposures and are thoroughly documented. For species with no 1-h AEGL, a Short Term Exposure Limit (STEL) from the American Conference of Industrial Hygienists (ACGIH, 2014), with the NIOSH STEL, OSHA STEL, and five times the TLV-TWA for the compound as alternate c_{ref} depending on availability (OSHA, 2006, NIOSH, 1996). For the cancer risk hazard (HRC), the inverse of the inhalation unit risk factor (IUR) from IRIS (EPA, 2011) or CalEPA (CalEPA, 2003) was used for c_{ref}.

Because individual tire fire studies lack comprehensive species coverage, ratios were calculated from multiple studies (EPA, 1997; CalEPA, 2002; Downard et al., co-submitted), ranked within study, and then merged into a unified ranking. Because no tire fire study included some compounds such as formaldehyde, a laboratory study of pooled crude oil burning was also included (Lemieux et al., 2004).

2.3 Development of Air Quality Index (AQI) for tire fires

Air quality indices (AQI) are useful for communication of the level of hazard (Chen et al., 2013; Dimitriou et al., 2013; EPA, 2006; Gurjar et al., 2008; OEHHA, 2012). However, traditional AQI formulas have drawbacks when applied to an emergency fire situation – 1-h, 8-h and 24-h averaging time AQI are needed but are not available for all pollutants, and it is not clear how to account for the multi-pollutant nature of the smoke. Factors such as tire particulate toxicity and the high mutagenicity of tire fire smoke relative to wood smoke (Lemieux and Ryan, 1993; Lindbom et al., 2006) suggest that conventional indices may be insufficient for tire fire smoke. We propose an AQI formula for total air quality index (a_{tot}) from summation of the impacts from multiple pollutants:

$$a_{tot} = \left[a_{PM}^{p} + o_1^{p} + o_2^{p} + \cdots + o_m^{p} + u_1^{p} + u_2^{p} + \cdots + u_n^{p}\right]^{1/p} \qquad (2)$$

Equation 2 includes the concentrations of $PM_{2.5}$ (a_{PM}), m co-pollutants (o_m), and n unmeasured compounds (u_n). Summation is appropriate when pollutants share a common health effect and mode of action (Murena, 2004; Plaia and Ruggieri, 2011). In the case of the tire fire smoke, most of the pollutants are respiratory irritants, and we propose summation over the irritant compounds. The exponent (p) controls the nature of the summation process; as p increases, the summation becomes dominated by the highest air quality index in the summation. A fixed p value of 2.5 has been proposed (Kyrkilis et al., 2007), which heavily weights the maximum AQI. In this study, results from p exponents of both 1 and 2.5 are explored, and the main results and discussion are reported using a p exponent of 1.

The AQI values for all compounds were calculated using linear interpolation between AQI breakpoints (EPA, 2009). Breakpoints for $PM_{2.5}$ were from OEHHA (2012), which are based on the EPA NAAQS but extend to 8-h and 1-h averaging periods. The NAAQS-based SO_2 AQI breakpoints are adopted uniformly for 24-h, 8-h, and 1-h averaging times.

For all other species, NAAQS based thresholds are not available, and AEGL were used if available. A full complement of AEGL mixing ratios consists of 15 values, corresponding to 5 averaging times and 3 thresholds: AEGL-1 (defined in section 2.2), AEGL-2 (irreversible or other serious adverse health effects), and AEGL-3 (life-threatening). For some compounds, AEGL concentrations are not available, and the AQI breakpoints rely on STEL instead, as described in section 2.2. Due to the high concentrations involved in the tire fire, and the high STEL and AEGL of some compounds, linear extrapolation of AQI values in excess of 500 was performed.

SO_2 has NAAQS-based AQI breakpoints as well as AEGL values and a STEL. Therefore, it is used to translate from concentrations relative to AEGL or STEL (available for many compounds) to concentrations relative to an AQI (available for SO_2). Specifically, the AQI of pollutant i is calculated by

$$a_i = a_{SO2}(f_{AEGL}^{-1}(\overline{AEGL}_{SO2}, f_{AEGL}(\overline{AEGL_i}, c_i))) \quad (3)$$

where f_{AEGL} is a piecewise linear function with two inputs: (a) the 3 AEGL values of species i (denoted by the vector $\overline{AEGL_i}$), and (b) c_i. f_{AEGL} is 0 at c_i of 0, and 1, 2 and 3, respectively at concentrations of AEGL-1, AEGL-2, and AEGL-3. f_{AEGL}^{-1} is the inverse function that returns the concentration that will give a specific value of f_{AEGL}. For SO_2, the AEGL-1, 2, and 3 mixing ratios are 200, 750, and 30,000 ppb, respectively. The 1-h NAAQS (also the value for an AQI of 100) is 75 ppb, and the STEL is 250 ppb. Therefore, for SO_2, the AEGL-1, 2, and 3 values occur at AQI values of 224, 700, and 28,000, respectively, and the SO_2 STEL occurs at an AQI value of 256.

$PM_{2.5}$ was used as a tracer of the tire fire smoke. That is, we considered tire fire smoke by its $PM_{2.5}$ concentration (denoted PM_t), and then calculate the concentrations of all co-pollutants (e.g. SO_2, formaldehyde, VOCs) using the ratio of the co-pollutant emission factor to that of PM_t. The various AQI values are combined according to equation 2. An example 1-h AQI calculation is shown in Supplementary materials.

2.4 Dispersion modeling

Two dispersion models, Hazard Prediction and Assessment Capability model (HPAC) version 5.0 MB (Sykes and Gabruk, 1997) and AERMOD (EPA-454/R-03-004, September 2004 release 0726) (EPA, 2004) were run independently, with results first available beginning on May 30, the fourth full day of the fire. Both models were provided to the incident command group to help plan activities, and to understand potential impacts on populated areas (Holmes and Morawska, 2006; Kakosimos et al., 2011; Morra et al., 2009).

The Iowa National Guard's 71st Civil Support Team requested dispersion modeling from the Defense Threat Reduction Agency (DTRA). DTRA modeled the landfill fire as combustion of oil using the HPAC.

AERMOD (EPA-454/R-03-004, September 2004 release 0726) (EPA, 2004) was used with regional forecast meteorology (60 hour forecast) from the Weather Research and Forecasting model (WRF) 3.3.1 (Skamarock et al., 2008). The WRF configuration included 24 vertical layers from the surface to 5 km, 4 km horizontal resolution, ACM2 planetary boundary layer scheme (Pleim, 2007), and initial conditions and observational constraint from the North American Mesoscale Model. WRF profiles were processed for AERMOD using MCIP2AERMOD (Davis et al., 2008).

WRF/AERMOD simulated dispersion to a 100 m receptor grid from an area source covering the burning landfill cells. All receptors were placed 2 m above terrain height. In forecasting, the smoke $PM_{2.5}$ emission rate was set at 0.4 g/s (10 μg/m^2-s) to match early field observations of the plume (site BDR on May 30, 20:00). For retrospective modeling to reconstruct concentrations, the emission rate for smoke was adjusted to minimize the average of the absolute fraction errors of observed plumes. Specifically, the peak model concentration at the distance of the monitoring location was compared to the observed peak at 10 min averaging time (where available) or hourly average concentration. Cases with the modeled plume more than 40° away from the measurement location were excluded.

3. Results and Discussion

The fire was first reported during the evening of May 26, 2012. The impact of the landfill fire plume on individual stationary sites was episodic and depended strongly on wind direction, dilution, and emission rates that vary due to firefighting activities, temperature, and atmospheric conditions (Akagi et al., 2012; CalEPA, 2002; JCPHD, 2012; Kwon and Castaldi, 2009). The tire fire was declared under control and smoke emission was almost eliminated as of June 12, 2012. The plume was well-dispersed during a majority of the fire-affected period due to meteorology. During these periods, its influence was localized. Conversely, two stable periods with low boundary layer heights and significant smoke accumulation over more widespread areas were identified (June 1-3 and June 7-8). Chronology of weather, PM concentrations, sampler activities, and model highlights are found in Supplementary materials. Concentrations of $PM_{2.5}$, SO_2, and PAH were used to develop emission factors and are discussed in Downard et al. (co-submitted). VOC concentrations are reported in section 3.1 prior to their use in hazard ratio calculations.

3.1 VOC

A total of 54 VOCs were quantified from May 27 to June 2 in both background and impacted locations. Tire fires are known to be a major source of VOCs (Lemieux and Ryan, 1993). Table 3 reports a selected list of VOC concentrations in a representative plume-impacted sample taken on May 28 at 300 m from the fire with additional data in Supplementary materials. Significant increments in concentration over background were observed for many aromatic VOCs such as benzene, toluene, ethyl toluene, dimethyl benzene, xylene and styrene, as well as aliphatics (e.g., propane, butane). Fewer carbonyls were measured, but acrolein showed enhancement. Several hydrocarbon concentrations were below detection limit.

Benzene concentrations ranged from 0.05-0.07 ppbv in background samples and increased to 8.3 ppbv and remained elevated in some samples (e.g., 0.63 ppbv 8.0 km downwind). Toluene was present at 8.7 ppbv in the plume and 0.50 ppbv downwind. Synthetic rubber components butadiene and styrene are typically below detection limits in Iowa City but were 0.5-1 ppbv at 300 m from the fire. The benzene concentrations were well below a number of relevant reference concentrations, such as the OSHA STEL (1000 ppb), the ACGIH TLV-TWA (100 ppb), and the AEGL-1 (52,000 ppb, 1-h) but close to the lower ATSDR minimum risk level of 9 ppb (ATSDR 2013).

3.2 Identification of key pollutants from hazard ratio analysis

Calculated cancer and acute hazard ratios (HRA and HRC) are summarized in Tables 2 and 3, respectively, with details on ambient concentration measurements and reference concentration values, from multiple studies in Supplementary materials. Acute hazard ratios can be found in the parenthesis in Table 2. Note that hazard ratios from different ambient concentration measurements (e.g., the Westley vs. the Iowa City VOCs) cannot be directly compared to each other or to the hazard ratios based on emission factors. Only the relative orderings can be compared. SO_2, $PM_{2.5}$, black carbon (BC), and air toxic VOCs had the highest rankings when assessed using concentrations or emission factors from Iowa City. In other studies with tire smoke, BC, biphenyl, benzene, benzaldehyde, PM, and CO were highly ranked hazards. SO_2, which receives the highest ranking by AEGL-based hazard ranking has limited published emission factors. For example, it is not listed as an emission factor in Lemieux and Ryan (1993); however, Lemieux and Ryan did publish an SO_2 and CO time series for a tire fire test that corroborates the high placement of SO_2 in our hazard ratio ranking. The test had an SO_2/CO mixing ratio of ~0.2-0.33 which corresponds to HRA_{SO2}/HRA_{CO} of 400-660.

Aldehydes have not been extensively measured in tire fire emissions, but are known components of smoke from burning oil. Aldehydes include strong irritants with low reference concentrations, and formaldehyde, benzaldehyde, and acrolein have high rankings according to their HRA. Accordingly, we expect these compounds to play a role in the health impacts of the smoke, and recommend further study of their emissions.

Hazard ratio rankings within an order of magnitude of each other were grouped to generate a merged ranked list of the most hazardous compounds found in the righthand column of Table 2. Compounds common to multiple studies (benzene, 1,3-butadiene, PM and CO) provided benchmarks for relative rankings. The unified acute hazard ratio for tire fires includes SO_2 > PM > BC> Acrolein, Formaldehyde > CO > Benzene, Benzaldehyde, Biphenyl, 4-Vinyl-1-Cyclohexene, and Phenol as the higher ranked compounds. Monitoring and risk assessment should prioritize compounds with high hazard ratios.

Table 3 lists the cancer hazard ratio results. These were calculated using two alternate methods. One method was to consider B[a]P, which has been used in past cancer risk screenings of tire fires, as well as gases for which there are URF values. The resulting ordering is B[a]P > benzene > 1,3-butadiene > naphthalene > formaldehyde > acetaldehyde > ethylbenzene. B[a]P has the highest HRC in all tire fire datasets examined, using a URF of 1.1×10^{-3} $(\mu g/m^3)^{-1}$. The alternate method is to also include tire fire $PM_{2.5}$ as a potential carcinogen, applying the diesel particulate matter URF [3.04×10^{-4} $(\mu g/m^3)^{-1}$, CalEPA, 2003]. In that case, the cancer risk is dominated by $PM_{2.5}$, as the $PM_{2.5}$ risk factor exceeds that of B[a]P by more than 2 orders of magnitude. Future research and cancer screenings should consider this more conservative approach of treating the PM in tire fire smoke as a carcinogen.

3.3 Tire fire irritant smoke AQI

The 24-h AQI of tire fire smoke measured as $PM_{2.5}$ (PM_t) is shown in Figure 3. It is calculated for two values of p (1 and 2.5, respectively) in the absence of background PM. 26 $\mu g/m^3$ of tire fire smoke equates to an AQI of 100 using with p=1, which can be contrasted to the ambient $PM_{2.5}$ concentration of 35.4 $\mu g/m^3$ required for the same AQI. When tire fire smoke $PM_{2.5}$ is 26 $\mu g/m^3$, it is expected to contain 13 ppb of SO_2 and 3.4 ppb of benzene. The contribution to the AQI at that concentration was 80% from $PM_{2.5}$, 19% from SO_2, and 1% from other gases. The p=2.5 curve crosses the AQI 100 threshold at a PM_t concentration of 34.8 $\mu g/m^3$. Tabulated results from a tire fire irritant smoke calculation for a 1-h AQI at a PM_t value of 100 $\mu g/m^3$ can be found in Table 4, and a lookup table of AQI values as a function of tire fire smoke and ambient $PM_{2.5}$ is in Table 5. It is anticipated that an incident command team could use a lookup table such as Table 5, or an equivalent tool, during a fire response to interpret monitoring and/or dispersion modeling data.

Carbon monoxide and B[a]P were included in Table 3 but not in the AQI calculation because their health impacts do not include respiratory irritation. Carbon monoxide has serious health effects and should be considered during tire fires; however, using the emission ratios of this work, and the concentrations needed to reach levels equivalent to an AQI of 100, a tire fire smoke AQI for CO will be less than 10% of the value calculated from PM_t alone, and less than 17% of that calculated from SO_2 alone. H_2S is a respiratory irritant with a low AEGL-1 possibly in tire fire smoke (WDHFS, 2006). Its emission factor is largely unknown, and it is not included in reported AQI values from Iowa City, but including it using an emission factor derived from reported H_2S/CO ratios would increase the AQI values by about 5%. A detailed example of a tire fire smoke AQI calculation can be found in Supplementary Material.

Some factors may cause the AQIs presented in this work to be lower limits than those that could (and perhaps should) be calculated. These include the fact that (1) we treat tire fire smoke $PM_{2.5}$ the same as ambient $PM_{2.5}$ without any multiplier to account for its properties; (2) we neglect the impacts of the coarse fraction of tire fire smoke; (3) the AEGL-1 concentrations for many of the VOCs in this work are higher than other threshold concentrations that could also be justified. Counterbalancing these are the use of p=1 in AQI in the figures and tables of this work (besides Figure 3 which includes both), and the use of the NAAQS 24-h $PM_{2.5}$ value of 35.4 μg m^{-3} as a key threshold for the AQI when other higher thresholds could also be justified, such as the occupational limit of respirable dust, which ranges from 3-5 mg/m^3. We feel that summing over irritating components of the tire fire smoke (i.e., using p=1) is justified because it is a conservative, protective assumption, and furthermore, it counterbalances some of the factors listed above that serve reduce the AQI.

3.4 Application of AERMOD as an emergency response tool for landfill fire dispersion

The emission rate from the fire is a necessary parameter for quantitative dispersion modeling, and this was unknown during the initial days of the fire. Three particulate mass measurements at BDR (see Figure 1, May 30, Downard et al. co-submitted) were used to calculate a preliminary emission rate of 0.4 g/s to match observed plume impact. For retrospective assessment of ambient concentrations, this emission rate was scaled to minimize model error as described in the methods section, resulting in a minimum average absolute fractional error of 0.87 for a scaling factor of 3.6 (r^2 of model-observation pairs 0.61; model mean 26 μg/m^3; observation mean 19 μg/m^3; n=20).

Figure 4 maps AERMOD predicted tire fire smoke concentrations from May 26 - June 8, 2012 for the 1-h maximum (Fig. 4a) and 24 h maximum (Fig. 4b) $PM_{2.5}$. The 1-h maximum has an additional 2.6 multiplier to reflect potential temporal variability in emission rate, based on the ratio of the maximum to the average $PM_{2.5}$ emission factor in Downard et al. (co-submitted). The highest concentration in the 1-h map is 3900 μg/m^3 located at the landfill. AERMOD 1-h maximum concentration of tire fire $PM_{2.5}$ smoke for the study period at distances of 1, 2, 3, 5 and 10 km were 243, 131, 80, 55 and 26 μg/m^3, respectively. Likewise 8-h (not shown) and 24-h maximum concentrations at the same distances were 107, 42, 27, 15 (8-h) and 60, 25, 16, 9 and 4 (24-h) μg/m^3, respectively.

AQI values in Figure 4 were calculated for the p=1 case. Exposure risks within a radius of approximately 1.5 km from the fire were clearly in the unhealthy zone during at least 1 hour of the fire and smoke levels as far as 18 km downwind were also likely to exceed AQI values of 100 for at least 1 hour of the event. Risks based on 24-h max $PM_{2.5}$ concentration also suggest areas as far as 3.1 km from the fire reached an unhealthy AQI for sensitive subpopulations. The recommended action for such zones, according to the OEHHA air quality index, is to consider closing sensitive areas such as schools, and cancelling outdoor events. Air quality in areas further than 3 km downwind from the fire was moderate when considering 24 h and longer averaging time periods.

Based on the modelled $PM_{2.5}$ average for the duration of the tire fire, an increased cancer risk is calculated for B[a]P, the compound used in past tire fire cancer risk estimates, as well as $PM_{2.5}$. The B[a]P to $PM_{2.5}$ ratio in the smoke is $7x10^{-4}$ (Downard et al., co-submitted). At the most impacted location (1 km) from the fire, the modeled mean concentrations during the fire period were 5.5 μg/m^3 and 3.8 ng/m^3 of tire fire $PM_{2.5}$ and B[a]P, respectively. The corresponding potential cancer risks are $1.2x10^{-6}$ and $3.0x10^{-9}$, respectively. To compare, the cancer risk for B[a]P of $7.0x10^{-9}$ during the Blair Township tire fire was similar (Sidhu et al., 2006). The B[a]P assessments of Sidhu and in Iowa City were both below the common acceptable risk threshold of $1x10^{-6}$, while the value for $PM_{2.5}$ using the diesel PM URF, exceeded it. The applicability of the diesel particulate matter URF to PM_t has not been established, but is used here due to the lack of other information about the cancer risks of the PM components of tire fire smoke.

3.5 Lessons learned for emergency response and monitoring

Review of notable tire fires in the US and Canada indicates a wide variety of air quality responses during emergency situations. We offer some recommendations for emergency air quality response in Table 6. The recommendations are in part based on a local multi-agency retrospective review (JCDPH, 2012) of the public health response to the Iowa City fire.

With respect to what compounds to target for monitoring and monitor placement, <u>any</u> of the high hazard ratio compounds (e.g., SO_2, $PM_{2.5}$, CO, black carbon PM, formaldehyde, acrolein) are sufficient. Concentrations of unsampled pollutants can be estimated using emission ratios. For example, the AQI in this work uses emission factor ratios based on PM. An example of an expanded AQI reference table with pollutants other than $PM_{2.5}$ as the smoke tracer can be found in Supplemental Materials.

A distance of 1-3 km radius from the fire provides the most actionable data for the public health response. At this distance, the plume will have undergone initial dispersion and plume processing and will allow for measurement of the plume and background air. Additional monitoring within 1 km of the source can be added if warranted by public health concerns with respiratory protection for monitoring personnel. Monitoring can be added at specific locations that may be of interest to determine or verify population exposure.

Stationary monitoring at 24-h time resolution is listed in Table 6 as lower priority, and this designation requires explanation. 24-h time resolution samples are useful for verifying impacts on populated areas, but they are not spatially representative (for example see Figure 4) and do not permit estimation of source strength and dispersion model calibration unless the duration of plume impact periods is well known. VOC speciation is similarly listed in Table 6. Because of the modest impact that VOCs had in the hazard ratio and AQI analysis, we list them as lower priority. However, the VOC sampling can be an important part of the monitoring response. VOCs do serve as a tracer for the smoke, and measurements can confirm uncertain source profile estimates.

Ideally, both rapid sampling (instantaneous to 10 min integration) and integrated sampling at 1, 8 or 24 h averaging time should take place at fixed locations for assessing population exposure potential. We recommend that (i) <u>at least one compound</u> be measured by both short term methods (<10 min) and integrated sampling (1 to 24-h) <u>at the same location</u> during plume impaction event(s); and (ii) that short term samplers, such as grab measurements, be co-located and operated simultaneously for some samples. This sampling strategy has numerous desirable characteristics. It directly measures both background and plume concentrations (by the instantaneous and real-time instruments); it allows estimation of concentration impacts at longer averaging times (using integrated samplers); it allows intercomparison of instruments (thus permitting calculation of concentration ratios and/or emission factors); it spatially constrains the plume (via a network of fixed site real-time instruments); and it is well-suited for calibration or evaluation of dispersion models.

We recommend that concentrations from dispersion modeling and monitors be converted to an AQI scale that the incident command team has been trained on; concentration predictions without interpretation may not be actionable for local responders. In the absence of other data, we recommend a $PM_{2.5}$ emission rate of 5.3 g per kg of combusted tire (Downard et al., co-submitted) if the mass burn rate can be estimated, and 36 μg $PM_{2.5}$ $m^{-2}s^{-1}$ if not but the extent of the fire is known.

As reiterated in the FEMA tire fire manual and other documents (IWMB, 2002; OSFM, 2004; USFA, 1998), a pre-planning incident plan is critical for responding intelligently to any hazmat fire. Landfills utilizing shredded tires should preplan for a hazmat fire in the liner system. One potentially transferrable preplanning structure is North Carolina's multiagency Air Toxic Analytical Support Team, or ATAST (NCDAQ, 2014).

As highlighted in Table 6, pre-planning should include a scheduled exercise where multiagency response is simulated. Such exercises are critical for developing competence with the necessary sampling protocols, and at identifying problems in the emergency response, such as gaps in training, communication, incident command structure, or equipment. A scheduled exercise would deal with one item noted in the Iowa after action review: confusion on communication protocols for contacting state and federal resources, and uncertainty on the extent and nature of the federal response once contact was made. In the Iowa City event, the federal response was advisory (from EPA and DTRA), but in other tire fires EPA deployed equipment and personnel. The exercise should include predetermination of public health messages, distribution outlets, and public health protection measures (closures, cancellations, evacuations, etc.) relative to anticipated AQI level or other concentration-based action levels. Finally, it is important to identify agencies or service providers with equipment and expertise to implement or guide an air monitoring response, and to establish how resources will be procured (e.g., establish contracts or memoranda of understanding).

Several research needs were identified based on the Iowa incident and follow up analysis. Additional work is warranted on multiple pollutant risk assessment. Calibrated, low-cost, portable, and battery-powered monitors with wireless data reporting features are needed to streamline emergency monitoring network deployment. In terms of smoke composition, research needs include refinement of emission factors and their sensitivity to combustion conditions, with specific emphasis on H_2S, aldehydes, organic vs. elemental carbon, metals speciation, and organics speciation of total and size-resolved PM. Characterization of the mass distribution, deposition lifetime, and morphology of smoke particles is also needed. Finally, within the public policy and waste management community, reassessment of the costs, risks, and benefits of shredded tire landfill drainage systems is warranted given the potential fire and public health risk.

4. Conclusions

We have assessed the outdoor concentrations of pollutants generated from the 18 day 2012 Iowa City tire fire at a variety of averaging times. We estimated maximum concentrations (1-h) of tire fire $PM_{2.5}$ smoke at distances of 1, 5 and 10 km of 243, 55 and 26 μg/m^3, respectively. Likewise 24-h maximum concentrations at the same distances were 60, 9 and 4 μg/m^3, respectively. Use of hazard ratios to screen many components in the tire fire smoke, and adoption of a novel multi-pollutant AQI system for irritant smoke will improve decision support capabilities and streamline monitoring strategies. For example, the use of the AQI establishes that smoke concentrations reached unhealthy outdoor levels out to distances of 1.6 km and 11 km at 24-h and 1-h averaging times, respectively. The fire constituted a serious public health concern, and we report recommendations for responding to future comparable incidents – preplanning, monitoring, dispersion modeling, and future research needs. We stress that the emission rate, speciation, and meteorology of each tire fire are unique, and while we believe our findings are generalizable, the extent of variability, especially in emissions speciation, is not well quantified.

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Caption for figures and tables

Figures

Figure 1: Photograph of the Iowa City landfill fire, with smoke primarily from the burning shredded tire drainage layer

Figure 2: Map of the study area shaded by Census 2010 block group population density (persons/km^2). Symbols mark locations of air quality samples from mobile sampling (green triangles), VOC grab samples (yellow circles), and long-term $PM_{2.5}$ monitors (red circles). Concentric circles mark radii of 1.6 km (1 mi, red), 3.2 km (2 mi, yellow), and 6.4 km (4 mi, blue) from the fire location.

Figure 3: Relationship between $PM_{2.5}$ concentrations (x axis) and Air Quality Index (AQI) (y axis). Two $PM_{2.5}$ vs. AQI relationships from equation 2 are compared to the current US EPA $PM_{2.5}$ Air Quality Index.

Figure 4: WRF-AERMOD dispersion model results for the period May 30 – June 12, 2012. (a) 1-h maximum concentration of tire fire smoke (μg/m^3 $PM_{2.5}$); (b) 24-h maximum concentration of tire fire smoke (μg/m^3 $PM_{2.5}$); (c) 1-h maximum AQI (p=1); and (d) 24-h maximum AQI (p=1).

Tables

Table 1: Increment over background for EPA TO-12 and TO-15 VOCs in the tire smoke plume at various measurement sites.

Table 2: Cancer hazard ratios derived from concentrations or emission factors from this work and from other ambient and laboratory combustion studies.

Table 3. Ranked order of acute hazard ratios from multiple studies and unified ranked order list of hazard ratios. Numbers in parentheses are the hazard ratios (see text).

Table 4. Variables necessary for calculation of the multicomponent air quality index (AQI)

Table 5. AQI values (p=1) as a function of tire fire $PM_{2.5}$ smoke concentration and background $PM_{2.5}$ concentration. Colors correspond to ranges as follows: green 0-50 (good); yellow 51-100 (moderate); orange 101-150 (unhealthy for sensitive groups); red 151-200 (unhealthy); purple 201-300 (very unhealthy); maroon >300 (hazardous). An expanded table with smoke indicators other than $PM_{2.5}$ (e.g. CO, CO_2) can be found in the supplementary material.

Table 6. Recommended steps and detailed actions to respond to a large-scale urban fire.

Table 1.

Species	Method detection limit (ppbv)	Method of detection	Tire plume[a] ppbv	Background air[b] ppbv	Δ VOC[c] ppbv	Enhancement over background[e]	Enhancement relative to benzene ($\Delta VOC_i / \Delta VOC_{benzene}$)
Aromatic							
Benzene	0.17	GCMS volatiles, EPA TO-15	8.27	0.05	8.22	164	1
Toluene	0.16		8.64	0.05	8.59	172	1.0
Ethylbenzene	0.18		0.66	<0.18	0.48[d]	3	1.6E-02
m,p Xylene	0.26		2.03	<0.26	1.77[d]	7	4.0E-02
o-Xylene	0.11		0.62	<0.11	0.51[d]	5	2.7E-02
Styrene	0.1		0.59	<0.1	0.49[d]	5	2.9E-02
1,2,4-Trimethylbenzene	0.14		0.27	<0.14	0.13[d]	1	5.4E-03
1,3,5-Trimethylbenzene	0.16		0.14	<0.16	0.0	0	
Isopropyl benzene	0.07	To-12 Speciated non-Methane Organics	0.6	<0.07	0.53[d]	8	4.4E-02
m-ethyltoluene	0.08		1.53	0.12	1.41	12	6.8E-02
p-ethyltoluene	0.1		0.76	0.05	0.71	14	8.3E-02
m-dimethyle benzene	0.05		0.08	<0.05	0.03[d]	1	3.5E-03
p-dimethyl benzene	0.04		0.49	<0.04	0.45[d]	11	6.5E-02
Halocarbon compounds							
Carbon tetrachloride	0.33	GCMS volatiles, EPA TO-15	0.09	0.1	0	0	
Dichlorodifluoromethane	0.23		0.53	0.51	0.02	0	2.3E-04
Trichloroflurormethane	0.17		0.25	0.22	0.03	0	7.9E-04
1,1,2 Trichloro,1,2,2-trifluroethane	0.18		0.08	0.08	0	0	0.0E+00
Aliphatic compounds							
Acetylene	0.73	GCMS volatiles, EPA TO-15	0.72	0.12	0.6	5	2.9E-02
Propylene	0.16		5.54	<0.16	5.38[d]	34	2.0E-01
1,3 butadiene	0.24		0.91	<0.24	0.67[d]	3	1.6E-02
Ethane	0.03	To-12 Speciated non-Methane Organics	41.7	2.5	39.2[d]	16	9.1E-02
propane	0.1		20.4	0.59	19.81	34	2.0E-01
Butane	0.1		6.07	0.29	5.78	20	1.2E-01
Isopentane	0.08		3.67	0.3	3.37	11	6.5E-02
Hexane	0.18		1.1	0.08	1.02	13	7.4E-02
Nonane	0.05		0.37	0.21	0.16	1	4.4E-03
1-decene	0.08		2.58	0.15	2.43	16	9.4E-02

Decane	0.08		1.13	<0.08	1.05[d]	13	7.6E-02
Dodecane	0.08		0.13	<.08	0.05[d]	1	3.6E-03
Carbonyl compounds							
Acrolein	0.08	GCMS volatiles, EPA TO-15	1.5	<0.08	1.42[d]	18	1.0E-01
Terpenoid compounds		To-12 Speciated non-Methane Organics					
α-Pinene	0.06		0.08	0.1	0.02		
Isoprene	0.08		2.49	0.14	2.35	17	9.8E-02

[a]Tire plume sample is based on the VOC canister measurement 300 meters away from fire; [b]Background sample is based on the Iowa Pentacrest (06/01/2012, 15:20); [c] ΔVOC is tire plume minus background sample; [d] Minimum detection limit values were used for the calculate of delta;
[e] Enhancement is the ratio of ΔVOC over background concentration. For background concentration below MDL, MDL values were substituted for the background.

Table 2:

CAS Number	Species of Interest	Unit Risk Factor (URF) $[(\mu g/m^3)^{-1}]$	EPA Classification	Laboratory open tire fire burn EF ($mg\ kg^{-1}$)	HRC	Rank	Westley Tire Fire Conc. ($\mu g\ m^{-3}$)	HRC	Rank	This study (VOC canister) Conc. ($\mu g\ m^{-3}$)	HRC	Rank	This study (emission factors) EF ($mg\ kg^{-1}$)	HRC	Rank	Pooled Oil Burning EF ($mg\ kg^{-1}$)	HRC	Rank
	PM2.5	$3.0x10^{-4}$											5350	1.6	1			
71-43-2	Benzene	$2.9x10^{-5}$	A	2205	0.064	2	9.2	$2.7x10^{-4}$	1	26.4	$7.7x10^{-4}$	1				251	$7.3x10^{-3}$	1
91-20-3	Naphthalene [(a)]	$3.4x10^{-5}$	C	1195	0.041	3												
106-99-0	1,3-Butadiene	$1.7x10^{-4}$	B2	160	0.027	3	1.1	$1.9x10^{-4}$	2	1.5	$2.6x10^{-4}$	2						
100-41-4	Ethylbenzene	$2.5x10^{-6}$	D	632	0.0016	4				2.9	$7.2x10^{-6}$	3				10	$2.5x10^{-5}$	4
50-00-0	Formaldehyde	$6.0x10^{-6}$	B1													139	$8.3x10^{-4}$	2
75-07-0	Acetaldehyde	$2.7x10^{-6}$	B2													44	$1.2x10^{-4}$	3
50-32-8	Benzo(a) pyrene	$1.1x10^{-3}$	A	113.9	0.13	1	0.15	$1.7x10^{-4}$	2				3.56	$3.9x10^{-3}$	2	7	$7.7x10^{-3}$	1

(a) Volatile and semi-volatile phase

Table 3

Hazard Ratio	Study					
	This study, emission factors	EPA, emission factors	Pooled oil burn	This study, VOC Canisters	Westley, CA	Unified Ranking by Hazard Ratio*
Higher ↑	SO_2 (13,500)	PM_{10} (2980)	Acrolein (160), Formaldehyde (126)	Acrolein (49)	PM_{10} (11)	SO_2
	$PM_{2.5}$ (357)	CO (262)	CO (65)	Benzene (0.16)	BC (0.46) CO (0.5)	PM
	BC (138)	Biphenyl (52), Vinyl-cyclohenene (49), Benzaldehyde (38)	Benzaldehyde (2.5), Benzene (1.5)	Toluene (0.04)	Benzene (0.06)	BC
		Naphthalene (13), Benzene (15), Phenol (12)	Napthalene (0.6), Isovaler-aldehyde (0.3)	Ethylbenzene (0.02) Styrene (0.03), Xylene (0.02)	1,3-Butadiene (<0.01)	Acrolein, Formaldehyde
		Styrene (7.6), Indene (4.8), Ethylbenzene (4.4), Xylenes (3.6), Toluene (3.3)	Acetone (0.04), Xylene (0.04), TMB (0.05), Toluene (0.06)	TMB (0.002), 1,3-Butadiene (0.001)		*CO*
		TMB (1.2), Cumene (1.6), Limonene (1.2)	MEK (0.01), Nonane (0.003)			Benzene, Benzaldehyde, Biphenyl, Vinyl-cyclohexene,Phenol
		1,3-Butadiene (0.1)				Naphthalene, Isovaleraldehyde
						Styrene, Indene, Ethylbenzene,Toluene, Acetone, Xylene, TMB, Cumene, Limonene
↓ Lower						1,3-Butadiene, MEK, Nonane

*In the unified list (rightmost column), regular typeface indicates respiratory irritation or reduced lung function as part of the acute effect; italic typeface indicates that respiratory irritation or reduced lung function is NOT part of the acute effect. This is the case only for carbon monoxide.

Table 4.

Species	EF_i/EF_t	Concentration* for an individual pollutant AQI of 100 1 h	8 h	24 h	Method**	Fraction of total AQI at 100 µg/m^3, p=1, 1 h
$PM_{2.5}$	1.0	88	50	35	NAAQS	0.71
SO_2	1.33	0.075	0.075	0.075	NAAQS	0.282
Acrolein	0.0021	0.0112	0.0112	0.0112	AEGL	0.0035
Formaldehyde	0.026	0.34	0.34	0.34	AEGL	0.00273
Benzene	0.41	19.5	3.4	3.4	AEGL	0.00167
Vinylcyclohexene	0.021	0.186	0.186	0.186	est. STEL	0.00107
Benzaldehyde	0.124	1.50	1.50	1.50	STEL	0.00083
Biphenyl	0.062	0.96	0.44	0.44	AEGL	0.00097
Phenol	0.133	5.6	2.36	2.36	AEGL	0.00064
Naphthalene	0.223	5.6	5.6	5.6	STEL	0.00033
Styrene	0.121	7.5	7.5	7.5	AEGL	0.00016
Indene	0.063	5.6	5.6	5.6	STEL	0.00010
Ethyl benzene	0.118	12.4	12.4	12.4	AEGL	9.58E-05
1,2,4-Trimethylbenzene	0.154	52	16.9	16.9	AEGL	8.11E-05
Xylene, mixed	0.38	49	49	49	AEGL	7.74E-05
Toluene	0.47	75	75	75	AEGL	7.26E-05
Limonene	0.61	187	187	187	est. STEL	2.53E-05
Cumene	0.074	18.7	18.7	18.7	AEGL	3.52E-05
Acetaldehyde	0.0060	16.9	16.9	16.9	AEGL	8.57E-06
Isovaleraldehyde	0.00093	2.47	2.47	2.47	est. STEL	4.67E-06
1,3-Butadiene	0.0299	251	251	251	AEGL	2.34E-06
Acetone	0.0037	75	75	75	AEGL	9.14E-07
Methyl ethyl ketone	0.0013	75	75	75	AEGL	2.58E-07
Nonane	0.0024	375	375	375	est. STEL	5.38E-08
Hydrogen sulfide	0.22†	0.19	0.12	0.12	AEGL	0.05

*Units are µg/m^3 for $PM_{2.5}$, and ppm for all other entries

**est. STEL indicates the AQI breakpoints were based on the SO_2 breakpoints scaled to the ratio of the SO_2 STEL to an estimated species STEL (5 times TLV-TWA)

†H_2S was not included in the reported AQI in this work because the high uncertainty on its presence in the smoke. The 0.22 emission ratio is based on a single H_2S/CO reading detected downwind of a tire fire. See text for discussion.

Table 5.

1hr Avg. Tire Fire PM2.5 (μg/m³)	1hr Avg. Background PM2.5 (μg/m³) 0	10	20	30	40	50
0	0	13	26	39	52	62
1	2	15	28	42	54	64
2	4	17	30	44	55	65
3	6	19	33	46	57	67
4	8	21	35	48	59	69
5	10	23	37	50	61	71
10	21	34	47	59	69	79
20	41	54[b]	67	77	87	97
30	62	74[a]	84	94	104	114
50	99	109	119	129	139	149
100	184	194	204	214	222	225
200	281	284	286	288	291	293
300	330	333	335	337	340	342

8hr Avg. Tire Fire PM2.5 (μg/m³)	8hr Avg. Background PM2.5 (μg/m³) 0	10	20	30	40	50
0	0	23	45	64	82	100
1	3	26	48	67	85	102
2	6	29	52	69	87	105
3	9	32	54	72	90	107
4	12	35	57	74	92	110
5	15	38	59	77	95	112
10	30	53	72	90	108	125
20	61	79	97	115	132	150
30	87	105[c]	123	140	157	173
50	138	155	172	188	192	196
100	231	235	239	244	248	252
200	318	328	338	348	358	368
300	444	449	454	459	465	470

24hr Avg. Tire Fire PM2.5 (μg/m^3) \ 24hr Avg. Background PM2.5 (μg/m^3)	0	10	20	30	40	50
0	0	42	67	88	112	137
1	5	47	70	91	115	140
2	10	52[e]	73	94	118	143
3	15	54	76	97	121	146
4	20	57	79	100	125	150
5	25	60	82	103	128	153
10	49	75[d]	96	119	144	160
20	82	104	127	152	167	173
30	111	134	159	175	180	186
50	174	190	195	201	206	211
100	246	251	257	262	267	272
200	368	378	388	398	408	418
300	494	504	514	524	534	544

[a]Cell corresponding to the most exposed 1h period at the Hoover site (measurements)

[b]Cell corresponding to the most exposed 1h period at IA-AMS (measurements)

[c]Cell corresponding to the most exposed 8h period at the Hoover site (measurements)

[d]Cell corresponding to the most exposed 24h period at the Hoover site (measurements)

[e]Cell corresponding to the most exposed 24h period at IA-AMS (dispersion model)

Table 6 .

Step	Detailed Actions
Prepare	• Practice multi-agency response • Map important sites and monitor placement • Establish how monitors will be obtained and operated
Monitor	• HIGHER PRIORITY: Monitor 1-hr $PM_{2.5}$, SO_2, CO, black carbon, or PM_{10} 1-3 km from source in populated areas. *These data can be used to assess population exposure, evaluate smoke intensity, calculate AQI values, and allow for dispersion model calibration.* • LOWER PRIORITY: Monitor above < 1 km from source (see text); Collect samples for VOC analysis (see text); 24-hr monitoring (see text); particulate matter chemical speciation
Model	• Forecast plume intensity, position, and AQI using AERMOD or equivalent • Adjust emission rates using monitoring data
Interpret	• Calculate AQI • Issue public health statements

Figure 1: Photograph of the Iowa City landfill fire, with smoke primarily from the burning shredded tire drainage layer

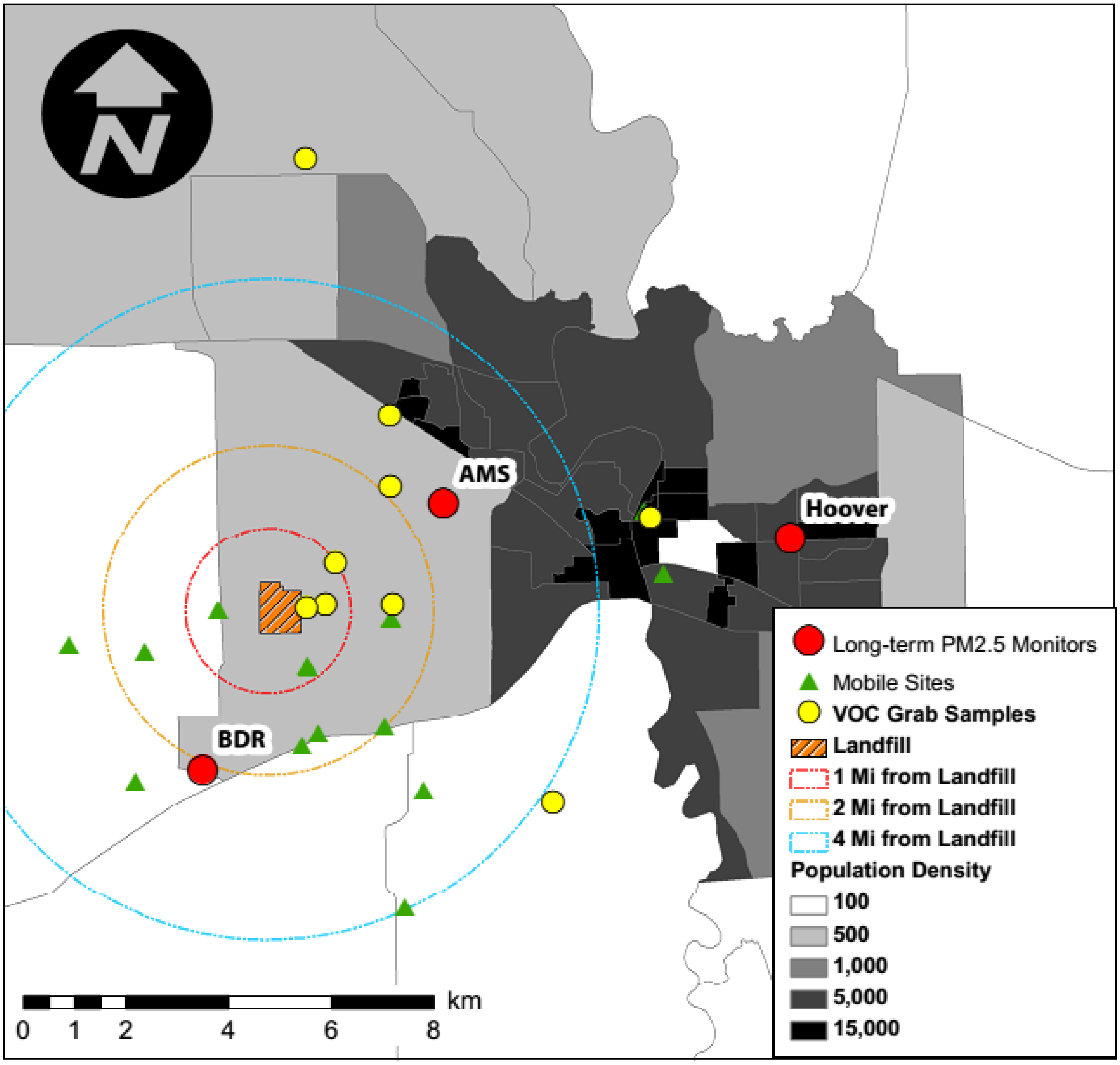

Figure 2: Map of the study area shaded by Census 2010 block group population density (persons/km^2). Symbols mark locations of air quality samples from mobile sampling (green triangles), VOC grab samples (yellow circles), and long-term $PM_{2.5}$ monitors (red circles). Concentric circles mark radii of 1.6 km (1 mi, red), 3.2 km (2 mi, yellow), and 6.4 km (4 mi, blue) from the fire location.

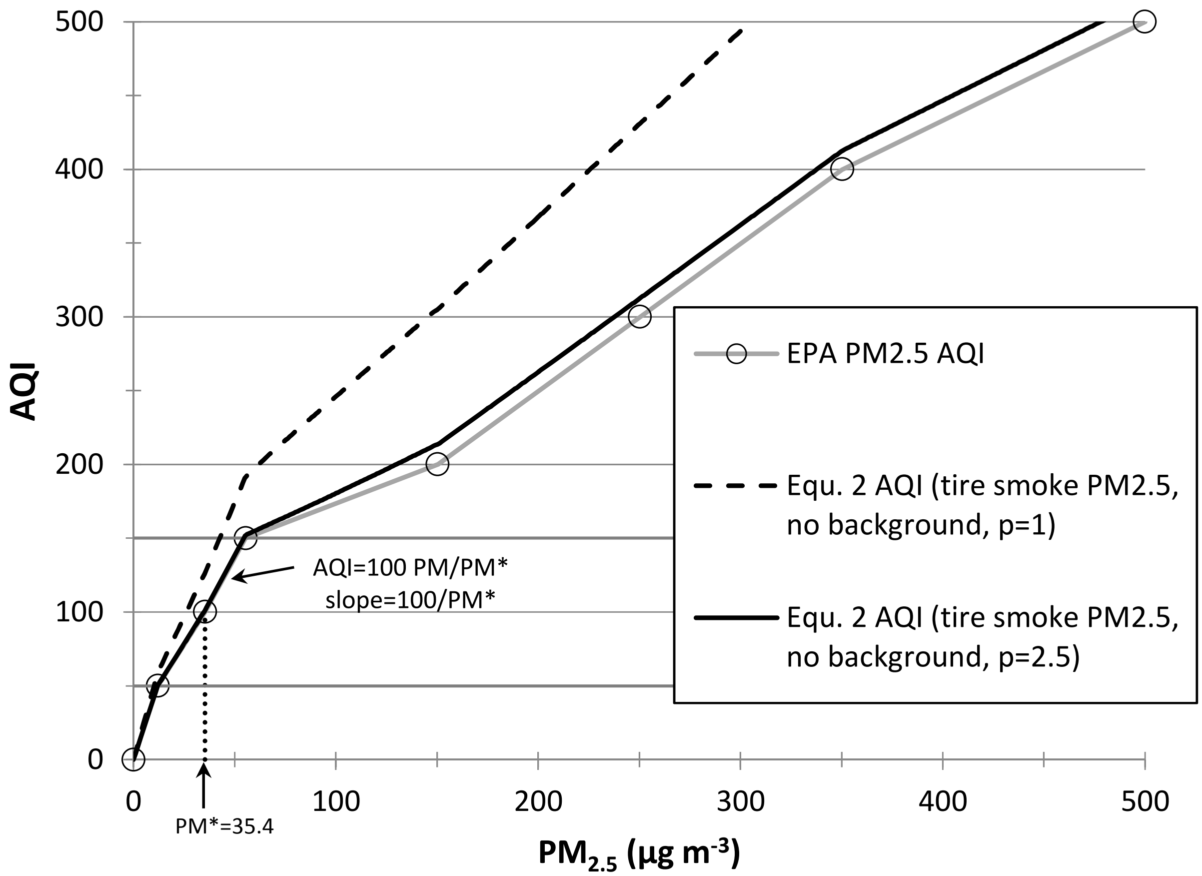

Figure 3: Relationship between $PM_{2.5}$ concentrations (x axis) and Air Quality Index (AQI) (y axis). Two $PM_{2.5}$ vs. AQI relationships from equation 2 are compared to the current US EPA $PM_{2.5}$ Air Quality Index.

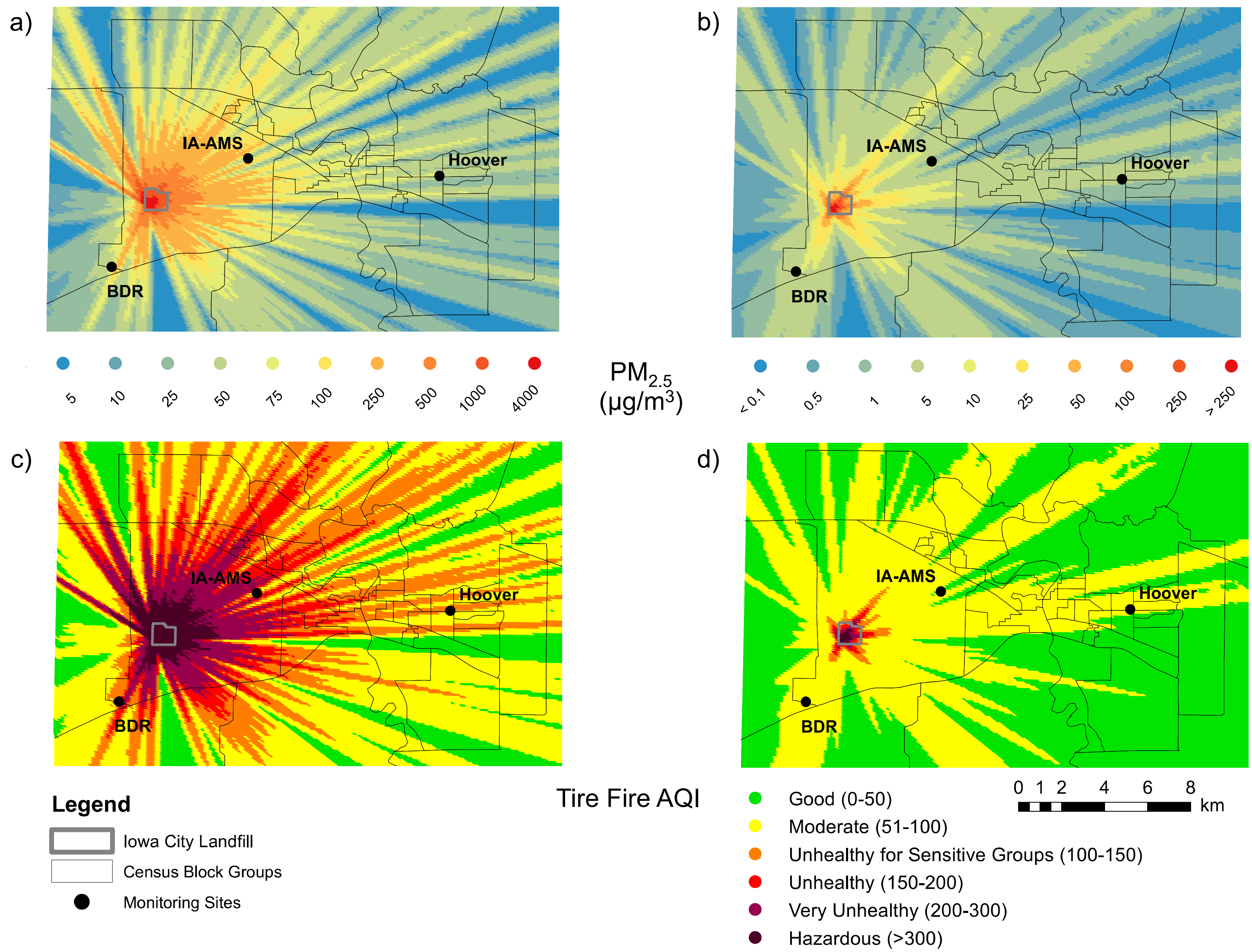

Figure 4: WRF-AERMOD dispersion model results for the period May 30 – June 12, 2012. (a) 1-h maximum concentration of tire fire smoke ($\mu g/m^3$ $PM_{2.5}$); (b) 24-h maximum concentration of tire fire smoke ($\mu g/m^3$ $PM_{2.5}$); (c) 1-h maximum AQI (p=1); and (d) 24-h maximum AQI (p=1)

Supplementary Material for

Uncontrolled Combustion of Shredded Tires in a Landfill

Part 2: Population Exposure, Public Health Response, and an Air Quality Index for Urban Fires

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Section 1: Chronology of the tire fire and response

The fire was first reported during the evening of May 26, 2012 under conditions of clear skies, low $PM_{2.5}$ levels, and warm temperatures. Initial winds were southeasterly, carrying the plume to the northwest and away from populated areas. Populated areas to the north of the landfill were first impacted on May 27, and then areas to the southeast of the landfill on May 28. The plume dispersed most efficiently from May 26 – 28, as indicated by retrospective dispersion modeling. Over the next few days, more stable atmospheric conditions led to higher concentrations of $PM_{2.5}$, measured up to 377 μg m^{-3} at 8.4 km from the fire on May 30.

High concentrations impacted populated areas in the north, and northeast on June 2 and 3 during periods of low wind speeds, low boundary layer heights, and increased atmospheric stability. The fire-related pollutants $PM_{2.5}$, SO_2, particle number, EC, and PAH peaked in Iowa City from June 1-3 (Downard et al., co-submitted). Dispersion improved on June 3, as boundary layer heights increased to over 2 km.

A "stir, burn and cover" operation began on June 4 to manage the fire. In general, the plume was dispersed very effectively from June 4 until June 7, and then had moderate impacts north of the landfill during June 7-10. Retrospective dispersion model classifies June 7-8 as the period 2nd least conducive to dispersion, but the June 7 and 8 plumes were not captured by monitors. The fire was declared under control and the emergency operation stopped on June 12. Additional detail on weather, PM concentrations, sampler activities, and associated AERMOD predictions are found in the following table.

Table S1. Chronology of Meteorology, Air Quality, and Air Quality Management Activities

Time period	Meteorology	Air Quality	Sampling, Forecasting, and Risk Management Activities
May 26 (Sat)	The fire was first reported during the evening (6:38 PM) of May 26, 2012. Conditions at the start of the fire were hot (high of 32°C), with clear skies and winds from the southeast. This carried the plume initially to sparsely populated areas to the northwest of the landfill.	Conditions at the start of the fire were clean ($PM_{2.5}$ of ~7 μg m^{-3}). Retrospective modeling shows the significant impact area (AQI>100, 1 h averaging time) extending a maximum distance of 1.3 km from the landfill.	Iowa City contacts Johnson County Public Health (JCPH) for public health concerns about smoke. JCPH contacts Linn County Public Health (LCPH) and the State Hygienic Laboratory (SHL).
May 27-28 (Sun-Mon)	Hot and clear or partly cloudy conditions continued on the 27th and 28th, but with shifting winds, first southerly winds which carried the plume into the populated Coralville area on May 27, and then westerly and northwesterly winds bringing the plume to a residential neighborhood and close to a school (Weber Elementary) on May 28.	The peak value of benzene sampled during the fire is taken: 8.3 ppb at 300 m away from the fire on the 28th. Retrospective dispersion modeling indicates excellent plume dispersion during this period. Maximum (modeled) peak 8 h smoke concentration in a densely populated area is in Coralville IA at ~0.6 μg/m^3 $PM_{2.5}$ smoke. Significant impact area (AQI>100, 8 h averaging time) is modeled to extend a maximum distance of 0.7 km from the landfill.	Public health advisory appears in the local newspaper.[1] JCPH in contact with the IDNR for technical assistance. TO-15 canister samples begin at 5:30 PM on May 27. May 27 is a 1-in-3 sampling day for the IA-AMS $PM_{2.5}$ speciation sampler. This sampler is changed to every day operation.
May 29-31 (Tue-Thu)	Conditions shifted to cooler (high of 27°C) on May 29 with strong northwesterly winds. Cool and windy conditions, with some rain, prevailed on the May 30 and 31, with wind directions from the north and east (and therefore carrying the plume away from the populated areas).	No impact of the fire on Iowa City, Coralville, or North Liberty is expected due to the wind direction; out of the plume, the 24 h PM_{10} filter (AMS site) reads 16 μg/m^3, while the Hoover $PM_{2.5}$ BAM averages 3.7 μg/m^3. Retrospective dispersion modeling has the plume to the south of the landfill for the entirety of this period, and the significant impact area (AQI>100, 8 h averaging time) modeled to extend up to 3.8 km to the southeast of the landfill. The Stanier group trailer achieves an interception of a well-diluted smoke plume at BDR on May 30 ($\Delta PM_{2.5}$ of 0.7 μg/m^3 on a 6.3 μg/m^3 background, 30 min average). A hand held Dust Trak reads an instantaneous reading of 377 μg/m^3 at a distance of 8.2 km from the fire.	Handheld surveys of $PM_{2.5}$ and CO begin. JCPH sends an official request (on 5/31) for State and Federal assistance in air monitoring and assessment. The Stanier group trailer is first deployed on May 29 but is just to the east of the plume and records clean conditions. The first SHL PM_{10} sample at IA-AMS is taken on May 30 and the first WRF-AERMOD and HPAC dispersion model forecasts are produced.

Time period	Meteorology	Air Quality	Sampling, Forecasting, and Risk Management Activities
June 1-3 (Fri-Sun)	On June 1-3, under cool conditions (highs of 20-27 C) light westerly winds threaten downtown Iowa City with landfill smoke and bring the plume to the IA-AMS and Hoover sites. This Friday – Sunday period is of special concern because an outdoor music festival is scheduled with large crowds in downtown Iowa City. Low boundary layer heights and neutral / stable conditions during some portions of this period.	Instantaneous $PM_{2.5}$ by Dust Trak is 510 $\mu g/m^3$ on June 1 at 2.4 km from the fire. June 2 is the day of the highest EC filter loading (AMS). PAH (24 h) is ~140 times background levels (AMS). During early morning of June 3, calm conditions and fog form, and high concentrations are recorded at the sites to the east of the landfill (1 h values of 48 and 71 $\mu g/m^3$ at AMS and Hoover, respectively). Reports of strong odor and respiratory irritation on the east side of Iowa City are noted. The retrospectively modeled area of significant impact (AQI > 100, 8 h averaging) extends farthest on the 2nd, out to 5.8 km from the landfill into Coralville, and 4.4 km towards Iowa City, crossing Mormon Trek Blvd. into the west side neighborhood of University Heights (but not reaching downtown Iowa City under 8 h averaging). Maximum 8 h modeled concentrations of smoke in downtown Coralville and downtown Iowa City are 16 and 6 $\mu g/m^3$, respectively.	Iowa City mayor signs a Local Disaster Declaration document (June 1) facilitating access to state and federal resources. Also on June 1, EPA region 7 personnel on site in Iowa City and participate in coordination meetings (SHL, JCPH, DNR, EPA) reviewing sampling activities and assessment. WRF-AERMOD forecasts shared with the JCPH predict poor dispersion, with hourly smoke concentrations in excess of 50 $\mu g/m^3$ in populated areas up to 9 km from the landfill. A plume transect experiment samples plume size distribution and number concentration at 3 distances.
June 4-7 (Mon-Thu)	From June 4-7, light easterly winds and favorable conditions for vertical plume dispersion prevail, carrying the plume up and away from populated areas. Heavy equipment operation at the landfill site begins on June 3 as part of the “stir burn and cover” operation and this creates a darker and larger smoke plume.	The highest instantaneous concentration of the fire period is recorded on a DustTrak instrument, 2000 $\mu g/m^3$ at a distance of 1.0 km under very smoky conditions during the morning of June 4. Upwind of the plume, the average $PM_{2.5}$ in Iowa City (Hoover) during this time is 9.4 $\mu g/m^3$ and the highest 1 h concentration is 21 $\mu g/m^3$. The modeled area of significant impact (AQI > 100, 8 h averaging) extends to 1.5 km to the northwest of the landfill.	WRF-AERMOD forecasts predicting excellent vertical dispersion of the plume are shared with JCPH. Handheld and TO-15 canister sampling is suspended.

Time period	Meteorology	Air Quality	Sampling, Forecasting, and Risk Management Activities
June 7-12 (Thu-Tue)	The evening of June 7 to June 10 brings southerly winds carrying the plume north towards Coralville and North Liberty. Conditions transition to westerly and northwesterly winds and cooler temperatures on June 11 and 12. The fire is declared fully under control and the stir, burn and cover operation is stopped on June 12.	Elevated EC concentration (AMS) on June 7, and the highest IA-AMS PM_{10} sample (29 $\mu g/m^3$) is taken on June 8. No visible smoke from the landfill as of June 12. The modeled area of significant impact (AQI > 100, 8 h averaging) extends to 3.9 km to the north of the landfill, towards North Liberty. A peak 8 h average concentration of landfill smoke of 2.7 $\mu g/m^3$ is modeled for the North Liberty library, 11.4 km from the landfill.	

1 (Source: Press Citizen) The Johnson County Health Department warns residents in the path of the smoke to avoid exposure to the smoke as much as possible. Persons who have respiratory, heart or other conditions which may be aggravated by smoke and the young and elderly should shelter in place with outside sources of air shut off. Most home air conditioning units recirculate air from the interior and should be sufficient. Businesses and other structures which draw in outside air should close outside air sources if the smoke plume is present. Avoid outdoor activities such as exercising if the smoke plume is present. Nursing homes, day cares and other businesses which care for the elderly, very young and persons with respiratory diseases should take special care to monitor the health of clients and to minimize exposure to the smoke plume.

By June 4, the public health advisory was unchanged in a press release by the City of Iowa City. However, the following two additional sentences were added: Concentration (increase and decrease) of particulate matter and other irritants in the smoke are greatly affected by weather conditions. Individuals are the best judges of their own health and should take appropriate protective measures based on their health status.

Section 2. Supporting Information on Measurement Location and Measurement Methods

Table S2. Measurement site information

Site	Latitude, Longitude	Distance to landfill site (km)	Observations	Dates
University of Iowa Air Monitoring Site (IA-AMS)	41.6647, -91.5845	4.2	Particle Size Distribution, PN, CO_2, SO_2, CO (6/1-6/4); $PM_{2.5}$ filters for speciation (05/27-06/10); PM_{10} mass (05/31-06/10)	see dates at left
Hoover Elementary Site[a]	41.6572, -91.5035	10.5	Continuous 1 h $PM_{2.5}$, 24 h $PM_{2.5}$ (gravimetric)	ongoing routine monitoring site
Black Diamond Road (BDR)	41.6188, -91.6422	3.2	Particle Size Distribution, PN, CO_2, SO_2, CO	05/30/2012-06/01/2012
Plume Transect				
1. Site A	41.6366,-91.6173	1.3	Particle size distribution, PN, BC	06/01/2012
2. Site B	41.6248, -91.6150	3.2	Particle size distribution, PN, BC	06/01/2012
3. Site C	41.6143, -91.5907	4.8	Particle size distribution, PN, BC	06/01/2012
Landfill	41.6469, -91.6194	0.3	VOC (TO-15, TO-12 Air Toxic)	06/01/2012
Community Samples				
Weber School	41.6472, -91.5969	2.4	VOC (TO-15 & 12)	5/28/2012
University of Iowa, Pentacrest	41.6614, -91.5361	7.6	"	06/02/2012
Camp Cardinal Rd.	41.6678, -91.5969	3.4	"	05/27/2012
Dane Road, SW	41.6117, -91.5605	6.7	"	06/01/2012
Slothower St.	41.6548, -91.6100	1.6	"	06/01/2012
First Ave. and 22nd Ave. Coralville	41.6803, -91.5967	4.5	"	05/27/2012
Forever Green Rd. and Route 965, N. Liberty	41.7257, -91.6151	8.3	"	05/27/2012

[a] EPA SLAMS Network in Iowa City for residential population exposure at Hoover Elementary School

Table S3: Characterization method overview, organized by sampling method (offline or real-time) and compound class

Analyte	Method and Instrumentation	Research Group[4]	Site(s)	Smoke Characteriztaion[2]	Numerical Emission Factor	Exposure Assessment[3]	Handheld	Hazard Ratio
TO-15, TO-12 VOCs	Collection in 6L canisters and GC/MS	SHL	Various	C		E, R		●
$PM_{2.5}$, PM_{10}	Beta Attenuation and Gravimetric filter (low volume)	SHL	Hoover ($PM_{2.5}$ & PM_{10}); IA-AMS (PM_{10})[5]			E, R		
$PM_{2.5}$ speciation (OC, EC, inorganic ions, metals and organic molecular markers)	Various, see text	Stone	IA-AMS	C	●	R		●
SO_2	UV fluorescence (Teledyne 100E)	Stanier	BDR, IA-AMS	C	●	R		●
CO_2	Infrared absorption (Vaisala 343 GMP)	Stanier	BDR, IA-AMS		●			
CO	NDIR absorption (Thermo 48i-TLE)	Stanier	BDR, IA-AMS	C	●			
CO	TSI 7575 Q-Track with electro-chemical CO sensor (IAQ-Probe Model 982)	JCPH	Various			E	●	
$PM_{2.5}$	Beta attenuation (BAM-1020)	SHL	Hoover			E, R		
$PM_{2.5}$	Light scattering photometer (TSI Dust Track-8532)[1]	JCPH	various			E	●	
Particle size distribution	Scanning Mobility Particle Sizer and Aerosol Particle Sizer	Stanier	BDR, IA-AMS, plume transect	P	●	R		●
Particle number (PN)	Condensation particle counter (TSI CPC 3786)	Stanier	BDR, IA-AMS, plume transect	P	●	R		

[1]Sensitive in to particles from 0.1-10 µm; [2]C indicates chemical characterization; P indicates physical characterization; [3]E indicates used mainly for exposure assessment during the incident; R indicates mainly used for retrospective assessment; [4] State Hygienic Lab (SHL), Johnson County Public Health (JCPH); [5]PM10 at IA-AMS is gravimetric mid volume sampler installed just for the tire fire period.

Section 3. VOC Sampling Methodology and Results Detail

Ambient VOC concentrations were determined by EPA methods TO-12 and TO-15 (EPA, 1999). Ten grab samples, representing background and plume-impacted air, were collected in pre-cleaned 6-L Summa canisters (Entech Silonite™). Analysis was by gas chromatography (GC) mass spectrometry (Agilent Technologies 7890A, 5975C; 60 m DB-1 column) with canister autosampler (Entech 7016), dynamic dilution (Entech 4600A), and pre-concentration (Entech 7100A). Each analysis used 500 cm^3 of sample and 100 cm^3 of internal standard, and thermal desorption into the GC by splitless injection. Initial calibration range for all 54 analytes was nominally 0.5 to 10 ppbv.

Table S4: All TO-15 and selected TO-12 VOC measured during the tire fire

	Species	Method detection limit	Method of detection	Coralville –End st/22nd Avenue	Iowa City- Camp Cardinal/Melrose	Iowa City near landfill	North Liberty, forevergreen road/965	Weber School, Iowa City	Iowa City Penta crest (not in plume)	Dane RD SW, Iowa city (in plume)	Iowa City, near fire	Slothower road, Iowa City (in plume)	Iowa City Penta crest (in plume)
		(ppbv)		05/27/2012/17:58	5/27/2012 18:11	5/27/2012 17:34	5/27/2012 17:40	5/28/2012 16:53	6/1/2012 15:20	6/1/2012 18:52	6/1/2012 15:32	6/1/2012 17:50	6/2/2012 7:00
	Aromatic												
1	Benzene	0.17		0.08	0.07	8.27	0.63	0.05	0.05	0.45	>10	0.08	0.18
2	Toluene	0.16		0.11	0.06	8.64	0.5	0.16	0.05	0.32	>10	0.11	0.15
3	Ethylbenzene	0.18		<0.18	<0.18	0.66	<0.18	<0.18	<0.18	<0.18	>10	<0.18	<0.18
4	m,p Xylene	0.26		<0.26	<0.26	2.03	<0.26	<0.26	<0.26	<0.26	>10	<0.26	<0.26
5	o-Xylene	0.11		<0.11	<0.11	0.62	<0.11	<0.11	<0.11	<0.11	10	<0.11	<0.11
6	Styrene	0.1		<0.1	<0.1	0.59	<0.1	<0.1	<0.1	<0.1	>10	<0.1	<0.1
7	1, 2 4-Trimethylbenzene	0.14		<0.14	<0.14	0.27	<0.14	<0.14	<0.14	<0.14	7.53	<0.14	<0.14
8	1, 3 5-Trimethylbenzene	0.16	GCMS volatiles, EPA TO-15	<0.16	<0.16	0.14	<0.16	<0.16	<0.16	<0.16	3.52	<0.16	<0.16
9	Benzyl Chloride	0.31		<0.31	<0.31	<0.31	<0.31	<0.31	<0.31	<0.31	<0.31	<0.31	<0.31
10	Chlorobenzene	0.13		<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	0.21	<0.13	<0.13
11	1,3 Dichlorobenzene	0.09		<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
12	1,4 Dichlorobenzene	0.1		<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
13	1,2 Dichlorobenzene	0.2		<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
14	1,2,4 Trichlorobenzene	0.23		<0.23	<0.23	<0.23	<0.23	<0.23			<0.23	<0.23	<0.23
	Halocarbon compounds												
15	Chloroform	0.11		<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11

	Species	Method detection limit	Method of detection	Coralville –End st/22nd Avenue	Iowa City- Camp Cardinal/Melrose	Iowa City near landfill	North Liberty, forevergreen road/965	Weber School, Iowa City	Iowa City Penta crest (not in plume)	Dane RD SW, Iowa city (in plume)	Iowa City, near fire	Slothower road, Iowa City (in plume)	Iowa City Penta crest (in plume)
		(ppbv)		05/27/2012/17:58	5/27/2012 18:11	5/27/2012 17:34	5/27/2012 17:40	5/28/2012 16:53	6/1/2012 15:20	6/1/2012 18:52	6/1/2012 15:32	6/1/2012 17:50	6/2/2012 7:00
	Tetrachloroethene	0.16		<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
16	Carbon tetrachloride	0.33		0.08	0.1	0.09	0.07	0.1	0.1	0.12	0.11	0.1	0.14
17	Dichlorodifluoromethane	0.23		0.51	0.51	0.53	0.5	0.56	0.51	0.61	0.56	0.48	0.65
18	Dichlorotetrafluoromethane	0.17		<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17
19	Chloromethane	0.3		0.62	0.64	0.59	0.54	0.67	0.71	0.66	0.67	0.59	0.74
20	Chloroethane	0.26		<0.26	<0.26	<0.26	<0.26	<0.26	<0.26	<0.26	<0.26	<0.26	<0.26
21	Trichloroflurormethane	0.17		0.23	0.24	0.25	0.22	0.24	0.22	0.26	0.24	0.19	0.3
22	1,1,2 Trichloro,1,2,2-trifluroethane	0.18		0.06	0.08	0.08	0.08	0.09	0.08	0.08	0.08	0.06	0.09
23	1,1 Dichoroethene	0.19		<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
24	Trans 1,2 Dichloroethane	0.14		<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
25	cis 1,2 Dichloroethane	0.22		<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22	<0.22
26	Chloroprene	0.13		<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13
27	1,1,1 Trichloroethane	0.27		<0.27	<0.27	<0.27	<0.27	<0.27	<0.27	<0.27	<0.27	<0.27	<0.27
28	1,1 Dichoroethane	0.07		<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07
29	1,2 Dichoroethane	0.09		<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
30	Trichloroethene	0.16		<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16
31	1,2 Dichloropropane	0.21		<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21
32	1,1,2 Trichloroethane	0.26		<0.26	<0.26	<0.26	<0.26	<0.26	<0.26	<0.26	<0.26	<0.26	<0.26

	Species	Method detection limit	Method of detection	Coralville –End st/22nd Avenue	Iowa City- Camp Cardinal/Melrose	Iowa City near landfill	North Liberty, forevergreen road/965	Weber School, Iowa City	Iowa City Penta crest (not in plume)	Dane RD SW, Iowa city (in plume)	Iowa City, near fire	Slothower road, Iowa City (in plume)	Iowa City Penta crest (in plume)
		(ppbv)		05/27/2012/17:58	5/27/2012 18:11	5/27/2012 17:34	5/27/2012 17:40	5/28/2012 16:53	6/1/2012 15:20	6/1/2012 18:52	6/1/2012 15:32	6/1/2012 17:50	6/2/2012 7:00
33	Bromodichloromethane	0.15		<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15
34	Dibromochloromethane	0.32		<0.32	<0.32	<0.32	<0.32	<0.32	<0.32	<0.32	<0.32	<0.32	<0.32
35	1,2 Dibromoethane	0.13		<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13
36	Bromoform	0.25		<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
37	Bromomethane	0.19		<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
38	1,1,2,2 Tetrachloroethane	0.2		<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
39	Hexachlorobutadiene	0.24		<0.24	<0.24	<0.24	<0.24	<0.24			<0.24	<0.24	<0.24
	Aliphatic compounds												
40	Acetylene	0.73		0.13	0.17	0.72	0.39	0.18	0.12	0.15	7.73	0.35	0.28
41	Propylene	0.16		<0.16	<0.16	5.54	0.91	<0.16	<0.16	0.26	>10	<0.16	<0.16
42	1,3 butadiene	0.24		<0.24	<0.24	0.91	<0.24	<0.24	<0.24	<0.24	8.13	<0.24	<0.24
43	Vinyle Chloride	0.18		<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18
44	Methly-t-butyl ether (MBTE)	0.12		<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
45	Ethly tert butly ether	0.19		<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
46	tert amyl methyl ether	0.21		<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21
47	Ethly acrylate	0.1		<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
48	Methyl methacrylate	0.14		<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
49	Cis-1,3 Dichloropropene	0.16		<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16
50	Trans 1,3 Dicholoropropene	0.17		<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17

	Species	Method detection limit	Method of detection	Coralville –End st/22nd Avenue	Iowa City- Camp Cardinal/Melrose	Iowa City near landfill	North Liberty, forevergreen road/965	Weber School, Iowa City	Iowa City Penta crest (not in plume)	Dane RD SW, Iowa city (in plume)	Iowa City, near fire	Slothower road, Iowa City (in plume)	Iowa City Penta crest (in plume)
		(ppbv)		05/27/2012/17:58	5/27/2012 18:11	5/27/2012 17:34	5/27/2012 17:40	5/28/2012 16:53	6/1/2012 15:20	6/1/2012 18:52	6/1/2012 15:32	6/1/2012 17:50	6/2/2012 7:00
51	Octane	0.14		<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
	Terpenoid compounds		To-12 Speciated non-Methane Organics										
52	α-Pinene	0.06		0.31	0.13	0.08	<0.06	<0.06	0.1	0.76	0.38	<0.06	<0.06
53	Isoprene	0.08		4.13	1.77	2.49	0.47	0.54	0.14	0.39	16.14	0.31	0.24
	Carbonyl compounds												
54	Acrolein	0.08	GCMS volatiles, EPA TO-15	0.17	0.17	1.5	0.24	0.14	<0.08	<0.08	1.7	<0.08	<0.08
55	Methly ethyl ketone	0.18		<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18
56	Methyl Isobutyl Ketone	0.16		<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	3.47	<0.16	<0.16
57	Ethane	0.03	To-12 Speciated non-Methane Organics	3.85	3.81	41.7	3.73	4.7	2.5	4.07	>20	2.5	3.07
58	propane	0.1		1.99	2.09	20.4	1.85	3.04	0.59	1.5	>20	0.59	1.68
59	Butane	0.1		1	1.06	6.07	0.74	1.4	0.29	1.08	>20	0.31	0.54
60	Isopentane	0.08		0.78	0.64	3.67	0.5	0.56	0.3	1.05	>20	0.37	0.75
61	Hexane	0.18		0.18	0.16	1.1	0.17	0.19	0.08	0.17	15.58	0.13	0.18
62	Nonane	0.05		0.11	0.07	0.37	<.05	0.17	0.21	0.16	5.39	<.05	0.06
63	Isopropyl benzene	0.07		<0.07	<0.07	0.6	<0.07	<0.07	<0.07	0.09	12.21	<.07	<.07
64	m-ethyltoluene	0.08		<0.08	<0.08	1.53	0.11	<0.08	0.12	0.22	>20	0.15	0.11
65	p-ethyltoluene	0.1		<0.1	<0.1	0.76	0.8	<0.1	0.05	0.15	>20	0.08	0.06
66	1-decene	0.08		0.11	0.09	2.58	0.09	0.09	0.15	0.17	>20	0.19	0.21
67	Decane	0.08		0.04	0.07	1.13	<0.08	<0.08	<0.08	0.11	18.3	0.09	<0.08

	Species	Method detection limit	Method of detection	Coralville –End st/22nd Avenue	Iowa City- Camp Cardinal/Melrose	Iowa City near landfill	North Liberty, forevergreen road/965	Weber School, Iowa City	Iowa City Penta crest (not in plume)	Dane RD SW, Iowa city (in plume)	Iowa City, near fire	Slothower road, Iowa City (in plume)	Iowa City Penta crest (in plume)
		(ppbv)		05/27/2012/17:58	5/27/2012 18:11	5/27/2012 17:34	5/27/2012 17:40	5/28/2012 16:53	6/1/2012 15:20	6/1/2012 18:52	6/1/2012 15:32	6/1/2012 17:50	6/2/2012 7:00
68	Dodecane	0.08		<0.08	<0.08	0.13	0.08	0.06	<.08	<0.08	3.4	0.03	<.08
69	m-dimethyle benzene	0.05		<0.05	<0.05	0.08	<0.05	<0.05	<0.05	0.19	1.75	<0.05	<0.05
70	p-dimethyl benzene	0.04		0.09	0.08	0.49	0.07	0.2	<0.04	<0.04	11.7	0.24	0.14

Section 4. Support on the acute hazard ratio calculation

Table S5. Acute hazard ratios derived from concentrations or emission factors from this work and from other ambient and laboratory combustion studies.

CAS	Species	TLV-TWA[a] (mg/m3)	STEL or Ceiling[b] (mg/m3)	AEGL-1 (1 hr, mg/m3)	EPA Lab burn[d]			Westley,CA tire fire[e]			This study, VOC canister			This study emission factor			Pooled oil burn[f]		
					EF (mg/kg)	HR	Rank	Conc. (µg/m3)	HR x1000	Rank	Conc. (µg/m3)	HR x1000	Rank	EF (mg/kg)	HR	Rank	EF (mg/kg)	HR	Rank
none	PM_{25}	3	-	-	-	-		-	-		-	-		5350	357 **	2	-	-	
7446-09-5	SO_2	0.65	0.66[i]	0.52	-	-		-	-		-	-		7090	13528	1	-	-	
630-08-0	CO	29	458	-	1.2E+05	262 *	2	229	0.50 *	2	-	-		-	-		30000	65 *	3
none	PM_{10}	10	-	-	1.5E+05	2980 **	1	557	11.1 **	1	-	-		-	-		-	-	
none	BC	3.5	-	-	-	-		8	0.46 **	2	-	-		2410	138 **	3	-	-	
71-41-2	Benzene	1.6	16[ii]	166	2205	13.3	7	9.2	0.055	3	26.4	0.16	2	-	-		251	1.5	5
92-52-4	Biphenyl	1.26	-	-	330	52 **	3	-	-		-	-		-	-		-	-	
100-40-3	Vinylcyclohexene	0.44	-	-	108	49 **	4	-	-		-	-		-	-		-	-	
100-52-7	Benzaldehyde	8.8	17.4[i]	-	664	38 *	5	-	-		-	-		-	-		44	2.5 *	4
91-20-3	Naphthalene	52	79[i]	-	1195	15.2 *	6	-	-		-	-		-	-		44	0.6	6
108-95-2	Phenol	19.2	60[iii]	58	714	12.4	8	-	-		-	-		-	-		-	-	
106-99-0	1,3-Butadiene	4.4	11.1[ii]	1482	160	0.108	14	1.1	7E-4	4	1.5	0.001	6	-	-		-	-	
108-88-3	Toluene	75	565[iii]	754	2519	3.3	12	-	-		32	0.04	3	-	-		42	0.06	7
100-41-4	Ethyl benzene	87	543[iii]	143	632	4.4	11	-	-		2.9	0.02	4	-	-		10	0.07	7
95-13-6	Indene	23.7	71[iv]	-	339	4.8 *	10	-	-		-	-		-	-		-	-	
100-42-5	Styrene	85	170[i]	85	646	7.6	9	-	-		2.51	0.03	4	-	-		-	-	
95-63-6	1,2,4-Trimethylbenzene	123	-	688	826	1.2	13	-	-		1.3	0.002	5	-	-		32	0.05	7

CAS	Species	TLV-TWA[a] (mg/m3)	STEL or Ceiling[b] (mg/m3)	AEGL-1 (1 hr, mg/m3)	EPA Lab burn[d]			Westley,CA tire fire[e]			This study, VOC canister			This study emission factor			Pooled oil burn[f]		
					EF (mg/kg)	HR	Rank	Conc. (µg/m3)	HR x1000	Rank	Conc. (µg/m3)	HR x1000	Rank	EF (mg/kg)	HR	Rank	EF (mg/kg)	HR	Rank
138-86-3	Limonene	557	-	-	3239	1.16 **	13	-	-		-	-		-	-		-	-	
none	Xylene, mixed	434	651[i]	564	2013	3.6	12	-	-		9.9	0.017	5	-	-		25	0.04	7
98-82-8	Cumene	246	-	246	398	1.62	13	-	-		-	-		-	-		-	-	
107-02-8	Acrolein	0.23	0.23[i,C]	0.07	-	-		-	-		3.4	49	1	-	-		11	160	1
50-00-0	Formaldehyde	0.37	2.46[ii]	1.11	-	-		-	-		-	-		-	-		139	126	2
590-86-3	Isovaleraldehyde	4.7	-	-	-	-		-	-		-	-		-	-		5	0.3 **	6
75-07-0	Acetaldehyde	45	45[i,c]	81	-	-		-	-		-	-		-	-		32	0.4	6
67-64-1	Acetone	1188	1782[i]	475	-	-		-	-		-	-		-	-		20	0.04	7
111-84-2	Nonane	1050	-	-	-	-		-	-		-	-		-	-		13	0.003 **	9
338-23-4	Methyl ethyl ketone	590	885[i]	590	-	-		-	-		-	-		-	-		7	0.01	8
50-32-8	B[a]P	-	-	-	114	-		0.15	-		-	-		3.6	-		7	-	

Abbreviations: Emission factor (EF); Concentration (Conc.), and Hazard ratio (HR)

*STEL used in place of AEGL; **5 x TLV used in place of AEGL; **(a)** ACGIH: Documentation of the Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs). 2014. A summary of recent values can be found at https://www.osha.gov/dsg/annotated-pels/tablez-1.html; **(b)** STEL or Ceiling values (c) are based on (i) ACGIH, (ii) OSHA (iii) NIOSH (iv) Australian STEL; **(d)** Shredded tire combustion in EPA (1997). Values also reported in Lemieux et al. (2004); **(e)** Westley tire fire - 1 hr max concentration from Westley Livingston site at 4-5 miles downwind of the tire fire. **(f)** Crude oil emission factor are taken from Lemieux et al 2004 , table 8, page 20 [values are based from the original research work of Booher and Janke 1999]

Section 5. Support of the Multi-Pollutant AQI

An example calculation of the 1-h AQI resulting from 300 μg/m^3 of tire fire smoke.

The result can be seen from Table 5, and is 330. But additional details regarding the calculation are shown here.

- 300 μg/m^3 of $PM_{2.5}$ at 1-h averaging time alone, with no copollutants, carries an AQI of 188
- SO_2 is co-emitted, and will be at a concentration of 398 μg/m^3, or 152 ppb. This has a 1-h AQI of 135 as calculated at http://www.airnow.gov/index.cfm/index.cfm?action=resources.conc_aqi_calc
- The the SO_2 AQI contribution as 134.9.
- With p=1, these combine to 323
- These two compounds represent 97.9% of the total AQI.

The remaining 2.1% contribution are from a number of VOC compounds (listed in Table 6).

One of them is benzene, and its contribution is detailed here.

Benzene is coemitted with a mass ratio (relative to $PM_{2.5}$) of 0.41, so it is present in a concentration of 124 μg/m^3, or 38.7 ppb. This is associated with a benzene AQI contribution of 0.21. This is calculated as follows.

1. The first AQI breakpoint of SO_2 at the 1-h averaging time is AQI 50, concentration of 91.7 μg/m^3, or 35 ppb.
2. The AEGL-1 (1-h) for SO_2 is 200 ppb.
3. The AEGL-1 (1-h) for benzene is 52 ppm, or 52,000 ppb.
4. We convert from 38.7 ppb of benzene to a fraction of AEGL-1. The result is 7.44×10^{-4}
5. We construct an "equivalent" SO_2 concentration using 7.44×10^{-4} x AEGL-1_{SO2}, or 0.15 ppb SO_2
6. We determine the AQI for 0.15 ppb SO_2 (which is 0.15/35 x 50 = 0.21 AQI points).

We note that the OSHA STEL is a factor 10.4 lower than the AEGL-1, and using it as the basis for the calculation would increase the impact of benzene somewhat.

Some pollutants don't have an AEGL-1. For example, biphenyl. It has an AEGL-2 of 9.6 ppm. The estimate of the airborne concentration of biphenyl is 18.5 μg/m^3 (2.9 ppb), so the equivalent SO_2 concentration would be the AEGL-2 of SO_2 (750 ppb) x 2.9 / 9600 or 0.23 ppb of SO_2. This would have an AQI of 0.23 / 35 x 50 = 0.33 AQI units which matches the calculated value.

Table S6. AQI Categories (from Wildfire Smoke A Guide for Public Health Officials; Revised July 2008, With 2012 AQI Values)

Category	Notes
Good 0-50	If smoke exposure is forecast, implement communication plan.
Moderate 51-100	Issue public service announcements (PSAs) advising public about health effects and symptoms and ways to reduce exposure. Distribute information about exposure avoidance.
Unhealthy for Sensitive Subgroups 101-150	If smoke event projected to be prolonged, evaluate and notify possible sites for cleaner air shelters. If smoke event projected to be prolonged, prepare evacuation plans.
Unhealthy 151-200	Consider closing schools, possibly based on school environment and travel considerations. Consider canceling public events, based on public health and travel considerations.
Very unhealthy 201-300	Consider closing some or all schools (newer schools with a central air cleaning filter may be more protective than older leakier homes). Cancel outdoor events (e.g., concerts, sporting events).
Hazardous	Close schools. Cancel outdoor events (e.g., concerts, sporting events). Consider closing workplaces not essential to public health. If PM level is projected to remain high for a prolonged time, consider evacuation of sensitive subpopulations

Table S7. Expanded version of Table 5 that includes additional tracers of the tire fire smoke (benzene, CO, and SO_2, 1,3 butadiene, acrolein, CO_2, and $PM_{2.5}$ B[a]P), using emission factor ratios. Additional columns can be added based on what measurements are available, using emission factor ratios, or Δconcentration ratios. These are prepared assuming p=1.

1-h Average Pollutant in Tire Smoke							1-h Average Background $PM_{2.5}$ ($\mu g/m^3$)					
Benzene (ppb)	Benzene ($\mu g/m^3$)	CO (ppb)	CO ($\mu g/m^3$)	SO_2 (ppb)	SO_2 ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	0	10	20	30	40	50
0	0	0	0	0	0	0	0	13	26	39	52	62
0.015	0.047	20	23	0.5	1.3	1	2	15	28	42	54	64
0.029	0.094	40	46	1.0	2.7	2	4	17	30	44	55	65
0.044	0.14	60	68	1.5	4	3	6	19	33	46	57	67
0.06	0.19	80	91	2.0	5	4	8	21	35	48	59	69
0.07	0.24	100	114	2.5	7	5	10	23	37	50	61	71
0.15[a]	0.47	199	228	5	13	10	21	34	47	59	69	79
0.29	0.94	398	456	10	27	20	41	54[b]	67	77	87	97
0.44[b]	1.4	597	684	15	40	30[c]	62	74[a]	84	94	104	114
0.7	2.4	996	1140	25	67	50[d]	99	109	119	129	139	149
1.5	4.7	1990	2280	51	133	100	184	194	204	214	222	225
2.9	9.4	3981	4560	102	266	200	281	284	286	288	291	293
4.4[e]	14	5971[f]	6840	152	400	300	330	333	335	337	340	342

[a]This row corresponds to the instantaneous benzene concentration measured at the Pentacrest (downtown Iowa City) on June 2 in a "not in plume / background" sample. Background $PM_{2.5}$ was ~10 $\mu g/m^3$ placing that hour in the "good" category. A background concentration of 0.05 ppb has been subtracted from the measured value.

[b]This row corresponds to the instantaneous benzene concentration measured in North Liberty on May 27, and at Dane Rd. on June 1. Background $PM_{2.5}$ was ~10 $\mu g/m^3$ placing those conditions in the "moderate" category. A background concentration of 0.05 ppb has been subtracted from the measured value.

[c]This row corresponds to the worst 1h datapoint from IA-AMS (based on measurements of $PM_{2.5}$). Background $PM_{2.5}$ was ~10 $\mu g/m^3$ placing those conditions in the "moderate" category.

[d]This row corresponds to the worst 1h datapoint from Hoover Elementary (based on measurements of $PM_{2.5}$). Background $PM_{2.5}$ was ~10 $\mu g/m^3$ placing those conditions in the "unhealthy for sensitive subpopulations" category.

[e]Both of the plume intercepts (May 28 and June 1) near the landfill (300 m from the landfill fire) had benzene in excess of 4.4 ppb, placing them in the "hazardous" category. The June 1 AQI is corroborated by acrolein and 1,3 butadiene (see h and i) while the May 28 has a much higher ratio of benzene to these other compounds (see g and h).
[f]This row corresponds to instantaneous CO measurements Kansas Ave. (1.0 km) from the plume under "very smoky" conditions on June 4. The CO concentration as a marker of the multipollutant mixture identifies the period as "hazardous" even though the health effect of CO itself is not considered in the AQI and the level of CO is below the TLV-TWA of 29,000 $\mu g/m^3$

1-h Average Pollutant in Tire Smoke							1-h Average Background $PM_{2.5}$ ($\mu g/m^3$)					
1,3 Butadiene (ppb)	1,3 Butadiene ($\mu g/m^3$)	Acrolein (ppt)	Acrolein (ng/m^3)	CO_2 (ppm)	CO_2 (mg/m^3 C)	$PM_{2.5}$ BaP (ng/m^3)	0	10	20	30	40	50
0	0	0	0	0	0	0	0	13	26	39	52	62
0.020	0.044	0.87	2	0.31	0.15	0.70	2	15	28	42	54	64
0.040	0.088	1.7	4	0.61	0.30	1.4	4	17	30	44	55	65
0.060	0.13	2.6	6	0.92	0.45	2.1	6	19	33	46	57	67
0.080	0.18	3.5	8	1.23	0.60	2.8	8	21	35	48	59	69
0.10	0.22	4.4	10	1.53	0.75	3.5	10	23	37	50	61	71
0.20	0.44	8.7	20	3.1	1.5	7.0	21	34	47	59	69	79
0.40	0.90	17	40	6.1	3.0	14	41	54[b]	67	77	87	97
0.60	1.3	26	60	9.2	4.5	21	62	74[a]	84	94	104	114
1.0[g]	2.2	44	100	15	7.5	35	99	109	119	129	139	149
2.0	4.4	87[h]	200	31	15	70	184	194	204	214	222	225
3.0	8.8	174	400	61	30	140	281	284	286	288	291	293
4.0[i]	13	262[j]	600	92	45	210	330	333	335	337	340	342

[g]This row corresponds to the instantaneous 1,3 butadiene measurement at the landfill edge on May 28, placing the sampling the "unhealthy for sensitive subpopulations" category. This conflicts with the benzene measurements (see note e).
[h]This row marks the acrolein MDL for the TO-15 sampling done during the Iowa City fire
[i]This row corresponds to the instantaneous 1,3 butadiene measurement at the landfill edge on June 1. This places the sample in the "hazardous category" and matches the determination based on benzene (note e) and acrolein (note j).
[j]The instantaneous acrolein at the landfill fire edge on June 1 exceeded this row's threshold by a factor of 6. This places the sample in the "hazardous category" and matches the determination based on benzene (note e) and 1,3 butadiene (note i).

8-h Average Pollutant in Tire Smoke							8-h Average Background $PM_{2.5}$ (µg/m^3)					
Benzene (ppb)	Benzene (µg/m^3)	CO (ppb)	CO (µg/m^3)	SO_2 (ppb)	SO_2 (µg/m^3)	$PM_{2.5}$ (µg/m^3)	0	10	20	30	40	50
0	0	0	0	0	0	0	0	23	45	64	82	100
0.015	0.047	20	23	0.5	1.3	1	3	26	48	67	85	102
0.029	0.094	40	46	1.0	2.7	2	6	29	52	69	87	105
0.044	0.14	60	68	1.5	4	3	9	32	54	72	90	107
0.06	0.19	80	91	2.0	5	4	12	35	57	74	92	110
0.07	0.24	100	114	2.5	7	5	15	38	59	77	95	112
0.15	0.47	199	228	5	13	10	30	53	72	90	108	125
0.29	0.94	398	456	10	27	20	61	79	97	115	132	150
0.44	1.4	597	684	15	40	30[k]	87	105[c]	123	140	157	173
0.7	2.4	996	1140	25	67	50	138	155	172	188	192	196
1.5	4.7	1990	2280	51	133	100	231	235	239	244	248	252
2.9	9.4	3981	4560	102	266	200	318	328	338	348	358	368
4.4	14	5971	6840	152	400	300	444	449	454	459	465	470

[k]This row corresponds to the worst 8-h period from Hoover Elementary (based on measurements of $PM_{2.5}$). Background $PM_{2.5}$ was ~10 µg/m^3 placing those conditions in the "unhealthy for sensitive subpopulations" category.

8-h Average Pollutant in Tire Smoke							8-h Average Background $PM_{2.5}$ ($\mu g/m^3$)					
1,3 Butadiene (ppb)	1,3 Butadiene ($\mu g/m^3$)	Acrolein (ppt)	Acrolein (ng/m^3)	CO_2 (ppm)	CO_2 (mg/m^3 C)	$PM_{2.5}$ BaP (ng/m^3)	0	10	20	30	40	50
0	0	0	0	0	0	0	0	23	45	64	82	100
0.020	0.044	0.87	2	0.31	0.15	0.70	3	26	48	67	85	102
0.040	0.088	1.7	4	0.61	0.30	1.4	6	29	52	69	87	105
0.060	0.13	2.6	6	0.92	0.45	2.1	9	32	54	72	90	107
0.080	0.18	3.5	8	1.23	0.60	2.8	12	35	57	74	92	110
0.10	0.22	4.4	10	1.53	0.75	3.5	15	38	59	77	95	112
0.20	0.44	8.7	20	3.1	1.5	7.0	30	53	72	90	108	125
0.40	0.90	17	40	6.1	3.0	14	61	79	97	115	132	150
0.60	1.3	26	60	9.2	4.5	21	87	105[c]	123	140	157	173
1.0	2.2	44	100	15	7.5	35	138	155	172	188	192	196
2.0	4.4	87	200	31	15	70	231	235	239	244	248	252
3.0	8.8	174	400	61	30	140	318	328	338	348	358	368
4.0	13	262	600	92	45	210	444	449	454	459	465	470

24-h Average Pollutant in Tire Smoke							24-h Average Background $PM_{2.5}$ ($\mu g/m^3$)					
Benzene (ppb)	Benzene ($\mu g/m^3$)	CO (ppb)	CO ($\mu g/m^3$)	SO_2 (ppb)	SO_2 ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	0	10	20	30	40	50
0	0	0	0	0	0	0	0	42	67	88	112	137
0.015	0.047	20	23	0.5	1.3	1	5	47	70	91	115	140
0.029	0.094	40	46	1.0	2.7	2[l]	10	52[e]	73	94	118	143
0.044	0.14	60	68	1.5	4	3	15	54	76	97	121	146
0.06	0.19	80	91	2.0	5	4	20	57	79	100	125	150
0.07	0.24	100	114	2.5	7	5	25	60	82	103	128	153
0.15	0.47	199	228	5	13	10[m]	49	75[d]	96	119	144	160
0.29	0.94	398	456	10	27	20	82	104	127	152	167	173
0.44	1.4	597	684	15	40	30	111	134	159	175	180	186
0.7	2.4	996	1140	25	67	50	174	190	195	201	206	211
1.5	4.7	1990	2280	51	133	100	246	251	257	262	267	272
2.9	9.4	3981	4560	102	266	200	368	378	388	398	408	418
4.4	14	5971	6840	152	400	300	494	504	514	524	534	544

[l]This row corresponds to the worst 24-h period from IA-AMS (based on dispersion model of $PM_{2.5}$). Background $PM_{2.5}$ was ~10 $\mu g/m^3$ placing the category as "good." This is corroborated by B[a]P measurements (see note n).
[m]This row corresponds to the worst 24-h period from Hoover Elementary (based on measurements of $PM_{2.5}$). Background $PM_{2.5}$ was ~10 $\mu g/m^3$ placing those conditions in the "moderate" category.

24-h Average Pollutant in Tire Smoke							24-h Average Background $PM_{2.5}$ ($\mu g/m^3$)					
1,3 Butadiene (ppb)	1,3 Butadiene ($\mu g/m^3$)	Acrolein (ppt)	Acrolein (ng/m^3)	CO_2 (ppm)	CO_2 (mg/m^3 C)	$PM_{2.5}$ BaP (ng/m^3)	0	10	20	30	40	50
0	0	0	0	0	0	0	0	42	67	88	112	137
0.020	0.044	0.87	2	0.31	0.15	0.70	5	47	70	91	115	140
0.040	0.088	1.7	4	0.61	0.30	1.4[n]	10	52[e]	73	94	118	143
0.060	0.13	2.6	6	0.92	0.45	2.1	15	54	76	97	121	146
0.080	0.18	3.5	8	1.23	0.60	2.8	20	57	79	100	125	150
0.10	0.22	4.4	10	1.53	0.75	3.5	25	60	82	103	128	153
0.20	0.44	8.7	20	3.1	1.5	7.0	49	75[d]	96	119	144	160
0.40	0.90	17	40	6.1	3.0	14	82	104	127	152	167	173
0.60	1.3	26	60	9.2	4.5	21	111	134	159	175	180	186
1.0	2.2	44	100	15	7.5	35	174	190	195	201	206	211
2.0	4.4	87	200	31	15	70	246	251	257	262	267	272
3.0	8.8	174	400	61	30	140	368	378	388	398	408	418
4.0	13	262	600	92	45	210	494	504	514	524	534	544

[n]This row corresponds to the worst 24-h period from IA-AMS (based on 24-h B[a]P measurements). Background $PM_{2.5}$ was ~10 $\mu g/m^3$ placing the category as "good." This is corroborated by dispersion modeling (see note k).

Incident Name: Landfill Fire of 2012
Dates of Assignment: May 26 – June 9, 2012

After Action Review – Air Quality Monitoring Activities

EVENT SUMMARY –

At 6:38 pm on Saturday, May 26, the Fire Department responded to a call of a fire at the Iowa City Landfill, 3900 Hebl Ave., one mile west of Hwy 218 in Iowa City. The fire appears to have started at the working face of the landfill where garbage was dumped earlier in the day.

The fire then spread to the landfill liner system which includes a drainage layer of approximately 1.3 million shredded tires. Once the fire was in the drainage system, strong south winds spread it quickly along the west edge of the landfill cell.

Landfill staff used bulldozers to cut a gap in the shredded tire layer to contain the fire, but the fire spread across the gap before it could be completed. Staff regrouped and cut two additional fire breaks to halt the rapidly moving fire.

Protecting the health and safety of the public and workers onsite remained the number one priority for the City and all cooperating agencies as the tire shreds continued to burn. Also of primary concern was keeping the fire from spreading to adjacent landfill cells and to a portion of the new cell that was successfully isolated in the days following the fire's ignition. On June 1, Iowa City Mayor Matt Hayek signed a Local Disaster Declaration document. The declaration facilitated access to state and federal resources, including advanced air quality monitoring and thermal imaging technology to assist with mitigating the incident.

The Johnson County Health Department partnered with the State Hygienic Laboratory, Iowa Department of Natural Resources and subject matter experts with the University of Iowa to monitor air quality throughout the region. Officials with the United States Environmental Protection Agency were actively partnering with local and state officials on those issues related to air quality. The following precautions were issued to the general public:

Persons in the path of the smoke plume should avoid exposure to the smoke as much as possible. Persons who have respiratory, heart or other conditions which may be aggravated by smoke, pregnant women, and the young and elderly should shelter in places with outside sources of air shut off. Most home air conditioning units recirculate air from the interior and should be sufficient. Businesses and other structures which draw in outside air should close outside air sources if the smoke plume is present. Avoid outdoor activities such as exercising if the smoke plume is present. Nursing homes, day cares and other businesses which care for the elderly, very young, and persons with respiratory diseases should take special care to monitor the health of clients and to minimize exposure to the smoke plume.

On Tuesday, June 12, Environmental Restoration contactors completed a stir, burn, and cover strategy to finally contain the fire and stop the burning. Heavy equipment was in operation for a period of nine (9) days. Occasion flare-ups remain a possibility while overhaul operations are ongoing.

After Action Review (AAR)
Lessons Learned

The AAR is a tool that allows teams to learn from what they are doing and improve their performance. It is a structured discussion of specific events, inclusive of the entire team, and focused on learning from action to improve performance.

Lessons learned from the AAR discussion must be captured and put back into action and applied to performance quickly. The AAR is designed to help us understand why objectives were or were not accomplished, what really happened, what lessons can be learned, and how we can apply those lessons to improve performance.
AAR for Air Quality Activities:
June 27, 2012 1:00 – 3:00 pm
Johnson County Health and Human Services Building, Room 119D
Participants: Doug Beardsley and James Lacina, Johnson County Public Health; Scott Spak, U of I Environmental Policy Program at the Public Policy Center; Dave Wilson, JC Emergency Management Coordinator; Robert Bullard, U of I Dept. of Chemical & Biochemical Engineering; Betsy Stone and Jared Downard, U of I Dept. of Chemistry; Pam Kostle and Wanda Reiter-Kintz, State Hygienic Laboratory; Josh Sobaski and Kurt Levetzow, IA Dept. of Natural Resources (by phone); Shane Dodge, Linn County Public Health (by phone);

1. What was the most notable success at the incident that others may learn from? Please explain.

At the incident response level, use of the Incident Command System (ICS) was very instrumental in assuring that roles within the incident were understood and that information was shared and staff kept up-to-date on activities. Cooperation and willingness to help on the part of partner organizations was tremendous. Of particular note were the State Hygienic Laboratory and Linn County Public Health. Staff from both agencies were on the phone with JCPH early on (and late night) with offers to assist with air monitoring. We had DNR involvement which led to participation by EPA as well to offer technical assistance.

The learning curve, while steep, was handled well by all parties involved. Again, the success was due to the large number of resources and the infrastructure (internet, search engines, access to subject matter experts, teleconferencing, etc.) to access them. Staff at JCPH made the response a priority and had to juggle very full schedules from other duties in order to conduct the monitoring activities (as did staff from other agencies and organizations). This prioritization in order to address an emergency was appreciated.

The early development of a health message related to the smoke and the consistency of the message in light of research and air monitoring seemed to lend to the success of Iowa City's efforts and public information. The City was very open with information and very proactive with making information accessible to the public.

2. What were some of the most difficult challenges faced and how were they overcome? Please explain.

Since this was a new area in which JCPH did not have expertise, we tried to locate some sort of standard approach for monitoring a smoke plume. There was ample research on the constituents of tire fire smoke and some enlightening case studies of other large fires, but we could not locate a "how to" approach on monitoring. We proceeded with what made sense and shared that approach with local, state and federal partners for feedback. There was general consensus that our approach was good. We continued by sharing test results and continuously looked for feedback on monitoring strategies. It turns out that the strategy is fairly simple; drive in to the smoke at varying distances from the source and take samples. Most of our samples were "grab" samples. A better approach would be to take longer term samples to average out exposures. This challenge was overcome by doing what could be done and then being open with the public and being consistent and proactive with the message.

There was some initial confusion about who should be contacted and exact protocols to follow in order to access State and Federal resources. Early involvement of the County EMA was helpful, but sometimes there may have been parallel efforts aimed at the same resource. There was some confusion about "ownership" of SHL resources and how the DNR fit in to that. JCPH was not aware or did not understand the relationship of SHL capabilities and DNR funding of those services and whether or not SHL needed DNR acknowledgement to act. This may have been immaterial, however (no "need to know") as SHL secured whatever acknowledgements were needed. JC EMA was making requests but found that the feedback loop from State partners was inconsistent. This may have been complicated by too many people calling various duty officers (i.e. JCPH called the IDPH duty officer for assistance in contacting SHL and Linn CPH rather than directing all traffic via JC EOC.). Despite any confusion, there was no perceptible delay in deploying resources once we decided where we wanted to get samples. EMA and SHL will follow up to review who has what authorities and how we can streamline or reaffirm the correct notification procedures to secure air monitoring assets in the future.

While we would evaluate the air monitoring efforts as being successful, better coordination would have been welcome. JCPH was primarily coordinating the efforts and communicating with its partners who were providing testing services. Feedback during the AAR was that several strategy meetings with all air monitoring partners involved would have been helpful and may have changes how assets were deployed. Solution: in an incident of this magnitude in the future, staff up the air monitoring branch so a branch director is less involved in actual monitoring activities and has time to focus on coordination and strategy.

Additionally, there was some confusion or duplication when requesting Federal assets in the form of EPA assistance. When JCPH sent in a request for EPA assistance and then spoke with the EPA representative, other communication and/or requests had already been sent to EPA and they had already received deployment orders before speaking with JCPH. We appreciated their prompt response but there were some moments of concern about deployment and "what are they planning to do" on the part of JCPH. It turned out well in this case, which is the bottom line, but it caused a bit of unnecessary worry.

Another challenge or lesson learned was not being aware of and using the full capabilities for air monitoring which exists on the Hazmat vehicles. The Hazmat testing equipment was eventually deployed as the incident got in to the "stir, burn, and cover" activities. EMA will review these capabilities and ensure that they are listed as a resource for similar future events.

3. What changes, additions or deletions are recommended to augment agency training curriculums and/or operating policies?

As mentioned above, we will review our procedures for requesting assistance outside of our jurisdiction. We will review if we should pursue individual agreements with Linn County Public Health and the SHL or if current procedures working through the EOC are adequate to meet liability, reimbursement and other issues associated with receiving assistance. We will continue to train staff in the ICS and role of the EOC.

4. What issues were not resolved to your satisfaction and need further review? Based on what was learned, what is your recommendation for resolution?

There were no major issues which had not been resolved during the course of the incident or have not already been addressed above.

5. What remedies will the organization pursue and who will champion each initiative? If possible, attach timelines for completion.