Inhalation Toxicology

http://informahealthcare.com/iht
ISSN: 0895-8378 (print), 1091-7691 (electronic)

Inhal Toxicol, 2014; 26(10): 628–635
 DOI: 10.3109/08958378.2014.946633

informa
healthcare

RESEARCH ARTICLE

Outdoor wood furnaces create significant indoor particulate pollution in neighboring homes

David R. Brown[1], Nancy Alderman[2], Beth Weinberger[2], Celia Lewis[2], Jane Bradley[2], and Luke Curtis[3]

[1]Public Health Toxicologist, Wesport, CT, USA, [2]Environment and Human Health, New Haven, CT, USA, and [3]Medical Writer and Researcher, Burnsville, MN, USA

Abstract

Context: The use of outdoor wood furnaces (OWFs) is common in many parts of the United States. Little published information exists on the concentrations of outdoor and indoor fine particulates found near OWFs.

Objective: To compare $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) particle concentrations inside four Connecticut homes located 30.5–259 m from OWFs, and inside six Connecticut control homes located more than 2 km from the nearest OWF.

Materials and methods: $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) measurements were made with a Dylos light-scattering particulate counter.

Results: Mean $PM_{2.5}$ (cts) concentrations were 4.21 times as great in the four OWF exposed homes than the six control homes (0.302×10^6 counts/m^3 versus 0.0718 counts $\times 10^6$/m^3 $p < 0.001$). The mean $PM_{2.5}$ (cts) concentrations inside the four OWF exposed homes roughly corresponds to a mass $PM_{2.5}$ of 37 μg/m^3, which is above the US EPA 24-h $PM_{2.5}$ limit of 35 μg/m^3. Mean $PM_{0.5}$ (cts) concentrations were 3.44 times as great in the four OWF exposed homes than in the six control homes (0.657 versus 0.191×10^6/m^3 $p < 0.001$). Mean $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) concentrations were significantly higher in the house 259 m from an OWF as compared with the mean of the six control homes.

Conclusion: Existing regulations, such as the present Connecticut law requiring a 61 meter distance between an OWF and neighboring homes, are not adequate to protect the health of neighboring residents.

Keywords

Biomass burning, outdoor wood furnaces, particulates, $PM_{0.5}$, $PM_{2.5}$, wood burning

History

Received 6 May 2014
Revised 8 July 2014
Accepted 16 July 2014
Published online 21 August 2014

Introduction

Residential wood burning, whether for heating homes, food or water, produces large quantities of air pollutants. Depending upon the type of wood-burning device and the type of wood burned, burning a kilogram of wood will produce 1.6–21 g of fine airborne particulates, about 130 grams of carbon monoxide and about 4.1 g of methane (Gullett et al., 2003; Naeher et al., 2007; Schauer et al., 2001). Mixtures of at least 32 different poly aromatic hydrocarbons (PAHs) comprise an estimated 0.12–0.38% of wood smoke particulate (Gullett et al., 2003). Many of the PAHs found in wood smoke are highly carcinogenic (such as benzo(a)pryene) and are also found in tobacco smoke (Bostrom et al., 2002; Gullett et al., 2003).

Particles from wood smoke are particularly dangerous to humans since most of the particles are smaller than 1.0 μm in diameter and are easily inhaled deep into the lungs (Kleeman et al., 1999). Outdoor wood smoke particles have been shown to readily penetrate into homes and other buildings (Anuszewski et al., 1998). Many published studies have reported that in many towns and cities in the developed world, wintertime residential wood burning is responsible for 30–90% of the airborne fine particulates ($PM_{10.0}$ or $PM_{2.5}$) produced by all sources (Naeher et al., 2007). Residential wood burning produces about 90% of all airborne carbonaceous fine particles in rural New York State counties (New York State Department of Health, 2013). Wood burning-related particulate levels are usually highest from about 6 pm to 12 midnight when the highest rates of wood are burned (Ancelet et al., 2012). Wood burning produces large quantities of dark-colored heat-absorbing particulates, which are estimated to be a major driver in global climate warming (Chung et al., 2012).

Many human epidemiological studies have reported that exposures to higher levels of outdoor particulates and/or carbon monoxide are associated with significantly higher rates of asthma/COPD exacerbations, respiratory infections, myocardial infarctions, strokes, peripheral vascular disease and total mortality (Curtis et al., 2006). Some studies have examined the relationships between air pollution levels during heavy wood burning periods and respiratory health effects. A review of nine published studies compared ambient pollution levels and respiratory health outcomes reported

Address for correspondence: Luke Curtis, MD, MS, CIH, 12570 Portland Avenue South #223, Burnsville, MN 55337, USA. Tel: H 952-513-7568, C 847-769-4768. E-mail: LukeTCurtis@aol.com

during heavy wood burning periods in Washington and California, USA; British Columbia, Canada; and New Zealand (Boman et al., 2003). All nine of these studies reported that higher levels of particulates (measured as PM_{10}, $PM_{2.5}$ or PM_1) were associated with significantly greater rates of one or more adverse health outcomes including mortality, asthma symptoms, asthma hospitalization, emergency room visits or significantly poorer lung function tests (Boman et al., 2003).

In the past decade, there has been a tremendous growth in many parts of the United States of the use of outdoor wood furnaces (OWFs), also known as outdoor wood boilers (OWBs) and hydronic heaters. It was estimated that there were 155 000 OWFs in operation in the United States in 2005, with a projected 500 000 to be in operation in the United States by 2010 (New York Office of Attorney General, 2005).

An OWF is a wood-fired furnace usually housed in a small insulated shed located at least 6.1 m (20 ft) from a house. The OWF heats water, which is pumped to the house or building to be heated. OWFs can also be used to heat domestic water or swimming pools/hot tubs. OWFs operate with a hot cycle of combustion and a cool or idle cycle in which the damper is closed to cut off air supply. This idle cycle is a unique feature of OWFs, which produces cool particulate emissions which have little thermal buoyancy. OWFs range in capacity from 29 000 to 806 400 kcal/h (115 000–3 200 000 BTU/h) (NESCAUM, 2006). Most OWFs typically have short stacks 1.8–3.0 m (6–10 ft) in height (NESCAUM, 2006). A typical OWF has a heat efficiency of only 30–40% as compared to a modern wood stove efficiency of 60–80% (New York Office of Attorney General, 2005). Unlike most modern wood stoves, few OWFs have catalytic devices, which reduce pollutant emissions by oxidizing partially burned gases and particles (NESCAUM, 2006). See Figure 1 for a schematic drawing a typical OWF.

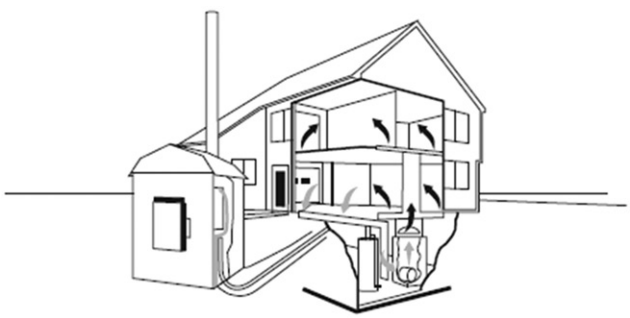

Figure 1. Schematic diagram of an outdoor wood furnace.

The air pollutants produced by OWFs are considerable. It is estimated that the average OWF produces as much fine particulates per hour as 22 EPA-certified wood burning stoves, 205 oil furnaces or 8000 natural gas furnaces (NESCAUM, 2006). A field study with a small 63 000 kcal/h (250 000 BTU/h) OWF reported that it produced a mean of 93 grams an hour of particulates during full operation and 64 g an hour of particulates during idle operation (NESCAUM, 2006). It was estimated that OWFs could produce about 873 000 metric tons of particulate matter annually in the United States by 2010, assuming 500 000 OWBs in operation by 2010 (NESCAUM, 2006).

OWFs can cause smoky conditions for many hundreds of meters downwind. A study using a small 180 000 BTU/h OWF reported that outdoor $PM_{2.5}$ levels often exceeded 400 $\mu g/m^3$ at areas 45.7 m from the OWF (NESCAUM, 2006). A New York State study reported that $PM_{2.5}$ concentrations were significantly higher in all five outdoor study sites located 45.7–207 m distant from the nearest OWF as compared to sites at least 762 m from the nearest OWF (New York State Department of Health, 2013). The significantly higher $PM_{2.5}$ levels were reported even in two sites, which were downwind from the OWF less than 5% of the time. No statistical $PM_{2.5}$ difference was reported between a sampling site 387 m from an OWF and the control sites (New York State Department of Health, 2013). A brief Michigan study of a house property line 54.9 ms (180 ft) from an OWF reported that outdoor $PM_{2.5}$ averaged 31 $\mu g/m^3$ between 5:52 pm on 25 March 2009 and 6:40 am on 26 March 2009. In a control house with no OWFs nearby, outdoor $PM_{2.5}$ averaged 1 $\mu g/m^3$ over the same period (Michigan Department of Community Health, 2009).

Smoke from OWFs can also create substantial visual haze for many hundreds of feet downwind. Please see Figure 2 for a photo of neighborhood smoke emanating from an OWF.

Although there is a moderate amount of published information about air pollutants produced by wood burning in general, there is relatively little information about the air

Figure 2. Photo of smoky conditions around an OWF in Connecticut on 30 August 2012.

pollutants produced by OWFs. Furthermore, information about how use of OWFs affects indoor air quality in neighborhood buildings that do not burn wood is lacking. Air pollution from OWFs has become a major health and political concern in many parts of the United States. All OWFs have been effectively banned in Washington State (Washington State Department of Ecology, 2013) and Oregon. They are also banned in a number of towns in Connecticut, New York, Massachusetts, New Jersey, Minnesota and Wisconsin (Environment and Human Health, 2010).

This study was conducted by EHHI in 2010 to measure the $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) particulate pollution inside homes located from 30.5 to 259 m from neighbors' OWFs in four communities in Connecticut, USA. Levels of $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) were also measured in six control homes located at least 2 km from OWFs. Please note, to distinguish our number count (cts) measures from the gravimetric measures, we will designate the particle counts as $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) to distinguish them from the gravimetric counts of $PM_{2.5}$ and $PM_{0.5}$.

Materials and methods

Selection of sample homes

EHHI chose four Connecticut homes to study from the pool of individuals who had contacted EHHI about their problems with smoke from neighboring OWFs. These four impacted families allowed researchers to come into their homes for sampling. The four houses in the study were between 30.4 and 259 m (100–850 ft) from an OWF. E. Before fine particulate measurements began in participants' homes, they completed a short questionnaire to provide background information about their homes and their health concerns (questionnaire available online from EHHI). In addition, forms were provided for participants to record indoor activities that might increase particles in the air (vacuuming, cooking and smoking).

The make and model of three of the four OWFs were unknown. The neighboring OWF to House C was located 73.1 m (240 ft) from a Central Boiler (Greenbush, MN) CL5346 OWF unit with a maximum heat output of 126 000 Kcal/h (500 000 BTU/h) (University of Alaska at Fairbanks, 2008).

Six control homes were also selected in Connecticut to serve as controls. None of these homes had any tobacco smokers or active wood burning during the sampling periods. A seventh home was also selected as a control, but was omitted from analysis after data was collected because one of the residents had smoked heavily in the house during the sampling periods. Mean $PM_{2.5}$ (cts) levels in this control home with a smoker was 0.263×10^6 cts/m^3 as compared to means of 0.0718×10^6 cts/m^3 in the six other control homes and 0.302×10^6 cts/m^3 in the four OWF homes.

Measures of fine particulate levels

Real-time measurements for both $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) were made in the four homes using a light scattering or laser particle counter called the Dylos air quality monitor 1100 Pro (Riverside, CA). This monitor provides particulate counts of $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) per 0.01 ft^3 (or 0.283 L) of air. The approximate minimum particulate size detected for 50% of the particles is about 2.5 microns for the $PM_{2.5}$ (cts) channel and about 0.5 microns for the $PM_{0.5}$ (cts) channel (Northcross et al., 2013). Therefore, our particulate $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) counts are a somewhat different measurement as compared to gravimetric or mass $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) measurements.

At each home, the Dylos 1100 Pro was stationed out of the way of traffic, but in a room that residents said was both exposed to the wood smoke and frequented by the family. Since cooking increases airborne particulate matter, kitchens were not monitored, although particles from the kitchen can travel to other areas of the house. Depending on the house, the monitor was set up either in a bedroom, a living room or a study. The monitor was hooked up to a laptop computer (either a Toshiba Protégé 7100 or a Presario). As the monitor continuously counted the particles, minute-by-minute data were stored on the computer via its HyperTerminal.

Participants were asked not to touch the monitor or the computer and to call the researchers any time they had concerns. At each house, monitoring began at noon of the first day. Researchers then downloaded the minute-by-minute data and the hourly readings mid-day the following day (Day 2). This provided 24 h of hourly average readings. After downloading both sets of data, the particle monitor was reset for the next 24-h period. Day 3 followed the same protocol. On day 4, the data were downloaded, and the equipment was then removed from the home. Particulate levels in six Connecticut control homes were also measured using the identical measurement protocol.

The OWF homes were sampled on the following dates (the dates refer to the days when the 24-h sampling was begun): House A, 19 January to 22 January 2010; House B, 24 January 10 to 27 January 2010; House C, 1 February to 4 February 2010; and House D, 1 February to 4 February 2010. The control homes were sampled on the following dates: House E, 20 February and 2 March 2010; House F, 03 March and 04 March 2010; House G, 18 December 2009; House H, 12 February 2010; House I, on 13 February, 14 February and 19 February 2009; and House J, 18 February 2001.

Estimating approximate $PM_{2.5}$ levels from $PM_{2.5}$ particulate counts

The Dylos air quality monitor DC 1100 uses light scattering and photodiodes to detect airborne particles. The Dylos monitor measures airborne particulate levels in counts and not in mass. Most air quality regulations and most published studies examining relationships between daily airborne particulates and health conditions express particulates in terms of mass per volume such as μg/m^3. The US EPA National Ambient (outdoor) Air Quality Standards for $PM_{2.5}$ is 35 μg/m^3 for 24 h or 12 μg/m^3 averaged over three years (US EPA, 2012). An approximate conversion factor is therefore useful to convert particulate counts to approximate particulate mass levels.

The method employed in this study was to calibrate the $PM_{2.5}$ (cts) counts taken from outdoor samples with reported $PM_{2.5}$ mass concentrations collected at a Westport, CT,

Department of Environmental Protection (DEP) air monitoring station. Outdoor $PM_{2.5}$ (cts) counts were collected with the Dylos monitor daily over a two-month wintertime period at a site in Westport, CT, about 400 m from the DEP site at a location of which had no known OWF's within 10 km. Relative humidity (RH) was generally below 40% of these wintertime measurements. These measurements were then compared to Connecticut Air Monitoring $PM_{2.5}$ mass data at a site 400 m from the place that the Dylos measurements were made. The approximate relationships could be expressed with the linear equation:

$$y = 0.4074x + 1.9048,$$

where y = approximate $PM_{2.5}$ μg/m^3 and x = counts/0.283 L

R^2 for standard curve 0.894.

By this method, 81.2 $PM_{2.5}$ counts/0.283 L or about 0.287×10^6 $PM_{2.5}$ counts/m^3 are approximately equivalent to the US EPA $PM_{2.5}$ limit of 35 μg/m^3. This method assumes that the particulate size and mass distribution reported inside the study and control homes were reasonably similar to those reported outdoors in a community with no OWFs nearby. A large percentage of particles from wood smoke are smaller than 1 μm (Kleeman et al., 1999). Therefore, the percentage of ultrafine particles may be relatively larger in wood burning areas as compared to non-wood burning areas. If the particulate size distribution were significantly different in the OWF and control homes, this could affect the estimated conversion factors from particulate number to mass.

We caution that this equation was developed under low humidity conditions in wintertime Connecticut. Relationships may be different under higher humidity conditions. Particles in the atmosphere can adsorb water on the surface and absorb water overall. This effect increases both the weight and size of the particles collected. The EPA method that collects particulate onto a filter dries the particulates collected and weighs at 30–40% RH (US EPA, 1998). An earlier study reported that light scattering by airborne particles begins to increase significantly at about a RH of 60% and increases very significantly above a RH of about 80% as compared to RH below 30% (Day et al., 2000).

All of our Dylos indoor measurements were made indoors under wintertime conditions of generally very low RH. We did not collect RH measurements for our indoor sampling. We performed additional calibration work in 2013 comparing $PM_{2.5}$ μg/m^3 mass measurements at the Westport DEP station to the Dylos $PM_{2.5}$ counts/0.283 L collected a few meters from the Westport station. During days of 20–40% mean RH, each $PM_{2.5}$ (cts)/(0.283 L) from the Dylos was equivalent to 0.35–0.45 μg/m^3 $PM_{2.5}$ in mass measurements. At an average daily RH of 70–80%, each $PM_{2.5}$/0.283 L count was equivalent to about 0.10–0.20 μg/m^3 of $PM_{2.5}$. (Please note, one count per 0.283 L is equivalent to 3532 counts per 1 m^3). Future Dylos calibration work employing RH measurements may produce more precise calibrations between particle number counts and particle mass measurements.

Statistical analysis

Means, medians and standard deviations of $PM_{2.5}$ (cts) and $PM_{0.5}$(cts) levels were calculated on an Excel® spreadsheet. Statistical differences between the control homes and the OWF exposed homes were then calculated using a two sample *t*-test with unequal variances as described by Rosner (1990). For Table 2(A and B), the mean $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) concentrations of all of the control home measurements were used for statistical comparison of the OWF homes. In similar fashion, the mean $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) concentrations of all of the OWF home measurements were used for statistical comparison of the all of the control homes. For Table 3(A and B), mean $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) concentrations were compared for the OWF and control homes. All of the comparisons between the control and OWF homes involved unequal variances as calculated by F values at $p = 0.05$. Two-tailed p values were calculated, for one tailed p values, please divide by two.

Results

The characteristics of the four homes and their residents are listed in Table 1. This table reports health problems reported by the residents. Table 2(A and B) report mean, median, range and standard deviation of $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) concentrations seen in the four OWF-exposed homes and six control homes. Table 3(A and B) report mean, median and standard deviation of $PM_{2.5}$ and $PM_{0.5}$ during various six-hour periods

Table 1. Characteristics of homes near outdoor wood furnaces.

	House A	House B	House C	House D
Distance to OWF in meters	259	30.5	73.1	36.6
Home area m^2	507	914	396	Unknown
Working fireplace or woodstove?	One Propane, one wood	Woodstove	No	No
Burns wood?	No	Not during monitoring	No	No
Smokers	No	No	No	1 Person, but does not smoke in house
No. of residents	3	4	4	4
Type of heat	Oil, baseboards	Oil radiators and baseboards	Electric	Oil. Forced air
Cooking stove	Electric	Gas	Electric	Electric
Near major road (Within one kilometer)	No	No	No	No
How situated relative to OWF	OWF is W, OWF a bit higher than house	OWF is N across street, downhill from house, which has slope behind.	OWF is NW and downhill from house	OWF is NNE and downhill relative to house

Table 2. PM counts $\times 10^6/m^3$ in the four OWF exposed and six control homes.

Home	Number of $PM_{2.5}$ (cts) samples	Mean $PM_{2.5}$ (cts) $\times 10^6/m^3$ (SD)	Median $PM_{2.5}$ (cts) $\times 10^6/m^3$	Range of $PM_{2.5}$ (cts) $\times 10^6/m^3$	*p* Significance[a]
A: $PM_{2.5}$					
House A	72	0.154 (0.159)	0.109	0.007–0.879	<0.001
House B	72	0.470 (0.341)	0.386	0.106–1.943	<0.001
House C	71	0.416 (0.321)	0.324	0.0211–1.741	<0.001
House D	72	0.170 (0.221)	0.0724	0.0212–1.215	<0.001
All samples of four OWF exposed homes A–D	287	0.302 (0.305)	0.223	0.007–1.943	<0.001
House E	48	0.0566 (0.0454)	0.0547	0.00353–0.166	<0.001
House F	47	0.0808 (0.126)	0.0283	0.00353–0.671	<0.001
House G	23	0.0755 (0.0568)	0.0671	0.00706–0.215	<0.001
House H	24	0.115 (0.0564)	0.115	0.0389–0.251	<0.001
House I	70	0.0518 (0.0389)	0.0441	0.007–0.169	<0.001
House J	24	0.0960 (0.0959)	0.00582	0.00353–0.336	<0.001
All Samples of six control homes	236	0.0718 (0.0770)	0.0547	0.00353–0.671	<0.001
Home	Number of $PM_{0.5}$ (cts) samples	Mean $PM_{0.5}$ (cts) $\times 10^6/m^3$ (SD)	Median $PM_{0.5}$ (cts) $\times 10^6/m^3$	Range of $PM_{0.5}$ (cts) $\times 10^6/m^3$	*p* Significance[a]
B: $PM_{0.5}$					
House A	72	4.63 (2.70)	3.82	1.49–13.4	<0.001
House B	72	10.0 (6.90)	8.00	2.09–30.0	<0.001
House C	71	5.54 (3.06)	4.77	1.94–22.2	<0.001
House D	72	6.09 (3.67)	4.97	1.62–16.9	<0.001
All samples of four OWF exposed homes A–D	287	6.58 (4.85)	4.98	1.49–30.0	<0.001
House E	48	0.960 (0.509)	0.792	0.402–2.63	<0.001
House F	47	1.89 (1.69)	1.41	0.463–9.08	<0.001
House G	23	2.87 (5.14)	0.883	0.335–24.1	0.01
House H	24	1.99 (6.38)	1.99	0.971–3.080	<0.001
House I	70	2.04 (2.24)	1.19	0.586–10.5	<0.001
House J	24	2.46 (2.93)	1.43	0.787–12.4	<0.001
All samples of six control homes	236	1.91 (2.40)	1.21	0.335–24.1	<0.001

[a]*p* Significance refers to OWF homes versus mean of control homes (two tailed) and control homes versus mean OWF homes. Two sampled t-test with unequal variances.

Table 3. PM counts $\times 10^6/m^3$ in control homes and homes exposed to outdoor wood furnaces during various times of the day.

	Six control homes located over 2 Km from OWFs			Four homes located 30.5–259 meter from outdoor wood furnaces (OWFs)			
Time	Number of $PM_{2.5}$ (cts) samples	Mean (SD) $PM_{2.5}$ (cts) $\times 10^6/m^3$	Median $PM_{2.5}$ (cts) $\times 10^6/m^3$	Number of $PM_{2.5}$ (cts) samples	Mean (SD) $PM_{2.5}$ (cts) $\times 10^6/m^3$	Median $PM_{2.5}$ (cts) $\times 10^6/m^3$	Significance *p* -2 tailed control versus OWF homes
A: $PM_{2.5}$							
All measurements	236	0.0718 (0.0770)	0.0547	287	0.302 (0.305)	0.223	<0.001
1 PM–6 PM	58	0.0821 (0.0583)	0.0671	72	0.292 (0.287)	0.252	<0.001
7 PM–12 midnight	60	0.0612 (0.0921)	0.0353	72	0.461 (0.334)	0.439	<0.001
1 AM–6 AM	59	0.0683 (0.0792)	0.0459	72	0.216 (0.317)	0.0759	<0.001
7 AM–12 noon	59	0.0761 (0.0745)	0.0530	71	0.240 (0.205)	0.183	<0.001
	Six control homes			Four homes located 30.5–259 meters from outdoor wood furnaces (OWFs)			
Time	Number of $PM_{0.5}$ (cts) samples	Mean (SD) $PM_{0.5}$ (cts) $\times 10^6/m^3$	Median $PM_{0.5}$ (cts) $\times 10^6/m^3$	Number of $PM_{0.5}$ (cts) samples	Mean (SD) $PM_{0.5}$ (cts) $\times 10^6/m^3$	Median $PM_{0.5}$ (cts) $\times 10^6/m^3$	Significance *p* -2 tailed control versus OWF homes
B: $PM_{0.5}$							
All measurements	236	1.91 (2.39)	1.21	287	6.58 (4.85)	4.98	<0.001
1 PM–6 PM	58	1.91 (1.62)	1.21	72	5.69 (4.56)	4.23	<0.001
7 PM–12 midnight	60	2.01 (2.62)	1.08	72	7.95 (4.80)	6.55	<0.001
1 AM–6 AM	59	1.65 (1.37)	1.26	72	6.00 (3.40)	4.91	<0.001
7 AM–12 noon	59	2.07 (3.42)	1.26	71	6.67 (6.07)	4.98	<0.001

of the day. These tables illustrate the diurnal variation of airborne particulate concentrations. Levels of $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) were highest in the evening hours when air stability is usually greatest and the OWFs may be used more.

A graphical representation of the $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) particulate levels are reported below in Figure 3(A and B). This house was selected for graphical representation since it was 259 m from the nearest OWF.

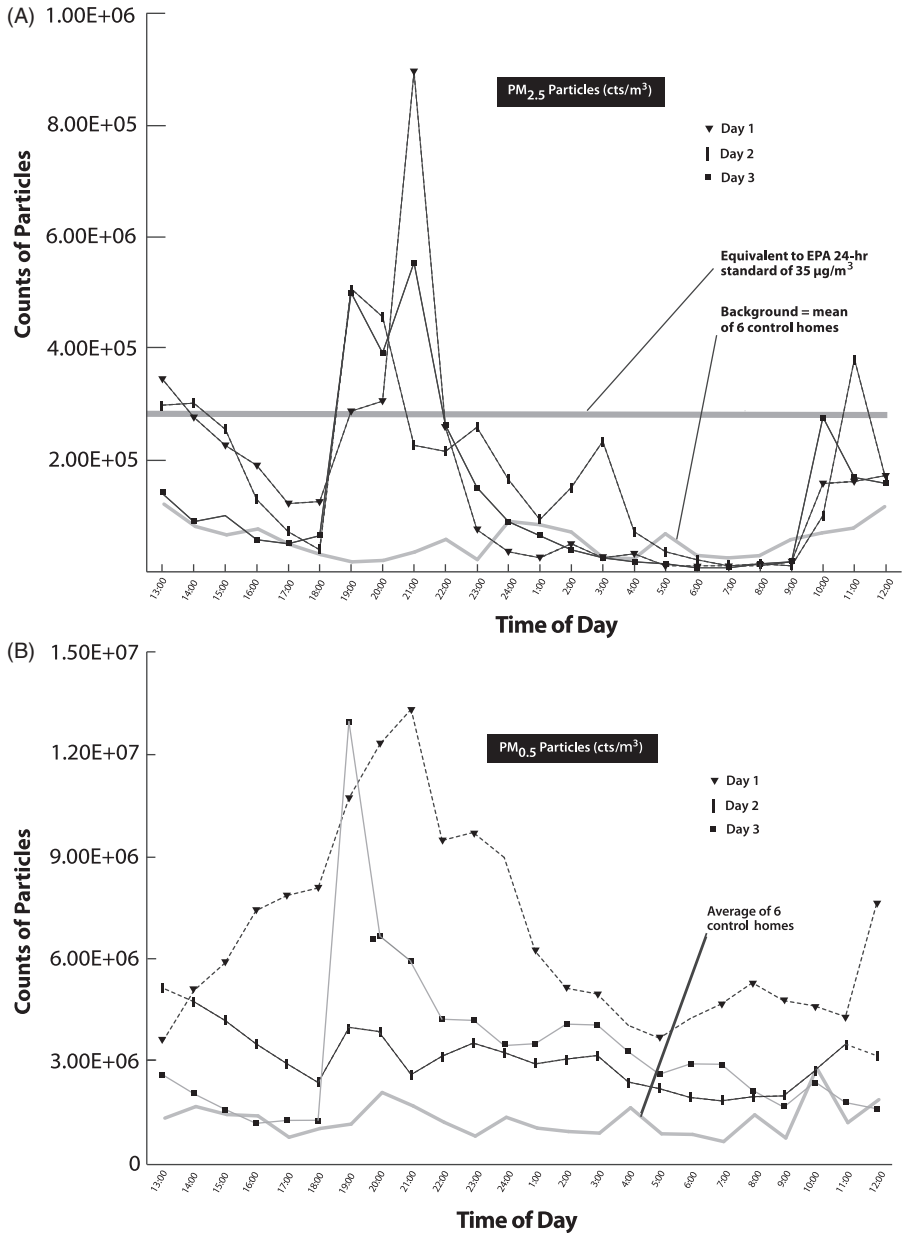

Figure 3. (A) Indoor $PM_{2.5}$ levels over a 24-h period at House A (259 m from an OWF) as compared with average of six homes not near an OWF. (B) Indoor $PM_{0.5}$ levels over a 24-h period at House A (259 m from an OWF) as compared with average of six homes not near an OWF.

Discussion

Particulate levels

The findings from this study indicate significant impact of OWFs on indoor particulate levels in homes as far away as 259 m in distance. Mean levels of both $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) were significantly higher in the four OWF exposed homes as compared to the six control homes. Compared to the control homes, mean $PM_{2.5}$ (cts) levels were 4.21 times as high in the OWF exposed homes (0.302 versus 0.0718×10^6 counts/m^3, $p < 0.001$) and mean $PM_{0.5}$ (cts) levels were 3.44 times as high in the OWF exposed homes (0.657 versus 0.191×10^6/m^3, $p < 0.001$). The mean $PM_{2.5}$ concentrations inside the four OWF exposed homes of 85.6 counts/0.01 ft^3 corresponds to about a $PM_{2.5}$ of about 37 µg/m^3, which is above the US EPA 24-h $PM_{2.5}$ limit of 35 µg/m^3.

Significantly higher mean levels of both $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) were reported at all four of the OWF exposed homes as compared to the mean of all six of the control homes (Table 2A and B). Among the individual OWF exposed homes, mean $PM_{2.5}$ (cts) levels averaged (in counts $\times 10^6$/m^3) 0.154 in House A (259 m from OWF), 0.470 in House B (30.5 m from OWF), 0.416 in House C (73.2 m from OWF) and 0.170 in House D (36.6 m from OWF). Please note that significantly elevated levels of both $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) existed even in House A – located 259 m from an OWF – which is much further than the 200 ft (61 m) requirement for OWF placement in Connecticut (2008) (Houses B and D were only 30.5 m and 36.6 m from an OWF installed before the 200 ft [60.9 m] Connecticut requirement and were grandfathered in). Distance from OWF has been used by state/local regulations as a protective device to protect the health of neighbors. However, the results of this study suggest these distances are insufficient.

Mean particulate levels varied greatly over the day in this study. Consistent with other studies in wood burning communities (Ancelet et al., 2012), mean indoor $PM_{2.5}$ (cts)

and $PM_{0.5}$ (cts) levels were higher during the period 6 pm to 12 midnight as compared to other times of day for both the OWF exposed homes and control homes (Table 3A and B). The higher fine particulate levels seen in the evening may be due to a number of factors including the following: (1) more wood may be burned during the evening than at other time periods, (2) other sources of indoor and outdoor pollutants such as cooking may be been more prevalent in the evening and (3) the dilution of outdoor air due to wind and the temperature/altitude gradients (atmospheric lapse rate) may have been less in the evening than during other periods during the day. These findings demonstrate the need for sampling over multiple periods over the day and illustrate the difficulty of identifying air pollution hazards by one inspection during working hours. Aggregate 24-h sampling may also not be adequate to determine health risks.

Mean levels of both $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) were significantly higher in the four OWF exposed homes are compared to the six control homes for each of the four six-hour periods tested (Table 3A and B). Mean $PM_{2.5}$ (cts) counts at the 6 pm to midnight time slot averaged $0.461 \times 10^6/m^3$. This corresponds to a $PM_{2.5}$ mass value of approximately $55\,\mu g/m^3$, or more than 1.5 times the US EPA 24-h $PM_{2.5}$ limit of $35\,\mu g/m^3$.

This research suggests that OWFs can produce harmful levels of airborne fine particulates inside neighborhood homes, even when the OWFs are in compliance with state regulations regarding operation and distance from homes on adjacent properties. Home A was located 259 m (850 ft) away from the nearest OWF, well above the 61 m (200 ft) requirement by Connecticut law (Connecticut, 2008); yet, indoor levels of fine particulates were significantly higher than the control homes. During evening hours, House A had indoor $PM_{2.5}$ equivalent levels which often reached 1.5–3 times the USA EPA 24-h limit of $35\,\mu g/m^3$ (Figure 1). Given that significant particulate elevations occurred in homes 259 m from an OWF, and given the effects of differing topography and OWF usage, we would be concerned with OWFs placed less than 777 m (three times 259 m) from neighboring homes.

Limitations of this study

This study has a number of limitations, including the relatively small number of OWF exposed and control homes, lack of on-site wind measurements and lack of monitoring for carbon monoxide and RH. Another possible limitation is that sampling for OWF exposed and control homes were not conducted on the same day. The very limited funding for this study precluded many of these measurements and the ability to test several homes simultaneously. However, the lack of overlap between mean statistical particulate concentrations between the four OWF and six controls suggest that there are substantial differences between particulate exposures in the OWF and control homes. Future, well-funded studies should sample larger groups of exposed and control homes, carefully measure meteorological parameters such as wind directions and speeds, temperatures and temperature/altitude gradients, humidity and prospectively examine respiratory health measures of community residents.

To our knowledge, the New York study (New York State Department of Health, 2013) is the first to examine outdoor air particulate levels at multiple sites near OWFs, while our study is the first to examine indoor air particulate levels near OWFs. The significantly higher $PM_{2.5}$ levels seen in the two New York study sites, which were downwind of the OWFs less than 5% of the time suggest that much of the wood smoke $PM_{2.5}$ may not travel on prevailing winds, and that citing homes upwind from OWFs may not protect occupants from high $PM_{2.5}$ levels (New York State Department of Health, 2013).

Ideas for future studies

Future studies should combine indoor and outdoor measurements of fine particulates near OWFs. Such a combined indoor/outdoor study should produce important data about air transport, house intrusion and exhaust and deposition of fine particulates from OWFs.

Most studies of airborne particulates in the past have relied either on air filter samples (which do not provide immediate results, require lab analysis and make it labor intensive to collect particulate filter samples every hour over a 24-h cycle) or use of expensive optical devices, which can cost many thousands of dollars. An inexpensive light-scattering airborne particulate counter, such as the Dylos meter (costing only about US $200), has already been in use for more than five years and may become increasingly useful in future studies involving real-time airborne particulate concentrations. Several published studies have validated that the $PM_{2.5}$ (cts) particulate counts can be accurately correlated with PM mass or $\mu g/m^3$ measurements (Northcross et al., 2013; Semple et al., 2013). RH of the air may have to be taken into account when converting particle counts into particle mass. Such particle counting meters can also be useful for citizens to measure indoor/outdoor $PM_{2.5}$ (cts) and $PM_{0.5}$ (cts) levels and to relate fine particulate levels with respiratory conditions such as asthma exacerbations. Such airborne particulate counters also enable citizens to measure and visualize changes in airborne particulate levels over time.

While such real-time light scattering instruments like the Dylos may be very useful for fine particle studies, it will still be useful to at least occasionally do filter-based particle collections to analyze for the composition of the particles. Real-time measurements for other wood smoke components such as carbon monoxide and polyaromatic hydrocarbons (PAHs) may also be useful for future studies on wood burning and health. Recently, a method was described that analyzed (PAHs) from wood stove smoke using a time-resolved, time-of-flight Aerosol Mass Spectrometry (Erikkson et al., 2014). This study reported that PAHs comprised about 1% of total organic particulate matter during slow burning pyrolysis conditions, but up to 40% of total organic matter during hot air-starved combustion conditions (Erikkson et al., 2014). Perhaps in the future, equipment and protocols can be developed that measure both total particulates and PAHs under real-time conditions.

More studies are needed to examine the relationships between reductions in wood burning pollution, improved indoor and outdoor air quality and reductions in adverse

health effects. There is need for studies examining the size distribution and indoor deposition of OWF emissions. There needs to be more medical and public awareness that OWFs and other forms of biomass burning can produce significant amounts of fine particulates, carbon monoxide and other toxins such as carcinogenic poly cyclic aromatic hydrocarbons such as benzo(a)pyrene. Such OWF-related air pollution can produce significant health risks, especially for respiratory and cardiovascular problems, and especially to vulnerable populations such as children, the elderly and those with pre-existing respiratory and cardiovascular conditions.

Conclusions

Most present regulations for OWF emissions and minimum distance from neighboring homes do not appear to be adequate to protect communities from high levels of fine air particulates. Better control strategies for minimizing OWF particulate pollution are clearly needed if public health is to be protected. Such OWF pollution control strategies could include the development of much cleaner burning and more energy efficient OWFs than have been developed so far, and only if this is possible with the existing OWF technology. Without significantly cleaner OWFs, switching homes to cleaner burning fuels such as natural gas, heating oil, use of renewable energy sources such as wind or active/passive solar or a combination of these options will better protect the public's health. If particulate emissions from current OWFs cannot be significantly reduced, then entirely banning OWFs becomes an option to consider.

Acknowledgements

We thank the 10 homeowners for allowing particulate sampling in their homes. We also thank the Connecticut DEP for the PM 2.5 $\mu g/m^3$ measurements.

Declaration of interest

None of the authors have any financial interest in companies making air particulate counters such as the Dylos Corporation (Riverside, CA).

The authors acknowledge funding from the Tortuga Foundation and The William Bullitt Foundation.

References

Ancelet T, Davy PK, Mitchell T, et al. (2012). Identification of particulate matter sources on hourly time-scale in a wood burning community. Environ Sci Technol 46:4767–74.

Anuszewski J, Larson TV, Koenig JQ. (1998). Simultaneous indoor and outdoor particle light-Scattering measurements at nine homes using a portable nephelometer. J Expo Anal Environ Epidemiol 8:483–93.

Boman BC, Forsberg AB, Jarvholm BG. (2003). Adverse health effects from ambient air pollution in relation to residential wood combustion in modern society. Scand J Work Health 29:251–60.

Bostrom CE, Gerde P, Hanberg A, et al. (2002). Cancer risk assessment, indicators, and guidelines for polycyclic aromatic hydrocarbons in the ambient air. Environ Health Perspect 110:459–83.

Chung CE, Ramanathan V, Decremer D. (2012). Observationally constrained estimates of carbonaceous aerosol radiative forcing. PNAS 109:11624–9.

Connecticut. (2008). Government Agency Report: Outdoor Wood Burning Boiler Laws, by P. Frishman. 2008-R-0310. Available from: http://www.cga.ct.gov/2008/rpt/2008-R-0310.htm. [Last accessed: 2 Jun 2013].

Curtis L, Rea WJ, Smith-Willis P, et al. (2006). Adverse health effects of outdoor air pollutants. Environ Int 32:815–30.

Day SM, Malm WC, Kreidenweis SM. (2000). Aerosol light scattering measurements as a function of relative humidity. J Air Waste Manage Assoc 50:710–16.

Environment and Human Health, Inc. (2010). The dangers to health from outdoor wood furnaces. Available from: http://www.ehhi.org/reports/woodsmoke. [Last accessed: 24 Feb 2013].

Erikkson AC, Nordin EZ, Nystrom R, et al. (2014). Particulate PAH emissions from residential biomass combustion: time-resolved analysis and aerosol mass spectrophotometry. Environ Sci Technol 48:7143–50.

Gullett BR, Touati A, Hays MD. (2003). PCDD/F, PCB, HxCBz, PAH, and PM emission factors for fireplace and woodstove combustion in the San Francisco Bay region. Environ Sci Technol 37: 1758–65.

Kleeman MJ, Schauer JJ, Cass GR. (1999). Size and composition distribution of fine particulate matter emitted from wood burning, meat charbroiling and cigarettes. Environ Sci Technol 33:3516–23.

Michigan Department of Community Health in Cooperation with Agency for Toxic Substances and Diseases Registry. (2009). Outdoor wood boiler investigation. Pleasant Lake, Jackson County, Michigan. Available from: http://www.atsdr.cdc.gov/hac/pha/OutdoorWoodBoilerInvestigation/OutdoorWoodBoilerInvestigation10-13-2009.pdf. [Last accessed: 2 Jun 2013].

Naeher L, Brauer M, Lipsett M, et al. (2007). Woodsmoke health effects: a review. Inhal Toxicol 19:67–106.

NESCAUM – Northeast States for Coordinated Air Use Management. (2006). Assessment of outdoor wood-fired boilers. Available from: http://www.nescaum.org/documents/assessment-of-outdoor-wood-fired-boilers [Last accessed: 24 Feb 2013].

New York Office of Attorney General. (2005). Smoke gets in your lungs: outdoor wood boilers in New York State, by J. Schreiber. Albany, New York. Available from: http://www.oag.state.ny.us/press/2005/aug/August%202005.pdf. [Last accessed: 25 Feb 2005].

New York State Department of Health, Bureau of Toxic Substances Assessment. (2013). Fine particulate matter concentrations in outdoor air near outdoor wood-fired boilers. Available from: http://www.health.ny.gov/environmental/outdoors/air/owb/docs/owb_report.pdf [Last accessed: 4 Feb 2013].

Northcross AL, Edwards RJ, Johnson MA, et al. (2013). A low-cost particle counter as a realtime fine-particle mass monitor. Environ Sci Processes 15:433–9.

Rosner B. (1990). Fundamentals of biostatistics. Boston, MA: PWS Kent Publishing, 248–92.

Schauer JJ, Kleeman MJ, Cass GR, Simmoneit BRT. (2001). Measurement of emissions from air pollution sources. 3, C1-C29 organic compounds from fireplace combustion of wood. Environ Sci Technol 35:1716–28.

Semple S, Apsley A, Maccalman L. (2013). An inexpensive particle monitor for smoker behavior modification in homes. Tob Control 22: 295–8.

University of Alaska at Fairbanks. (2008). Cooperative Extension Service. Available from: http://www.alaskawoodheating.com/boiler_-example.php. [Last accessed: 3 Mar 2014].

US Environmental Protection Agency (EPA). (2012). National Ambient Air Quality Standards (NAAQS). Available from: http://www.epa.gov/air/criteria.html [Last accessed: 23 Mar 2013].

US Environmental Protection Agency (EPA). (1998). Quality Assurance Guidance Document 2.12. Monitoring $PM_{2.5}$ in ambient air using designated reference or class I equivalent methods. Available from: http://www.epa.gov/ttnamti1/files/ambient/pm25/qa/m212covd.pdf. [Last accessed: 16 Nov 2013].

Washington State Department of Ecology. (2013). Wood fired hydronic heaters. Available from: http://www.ecy.wa.gov/programs/air/outdoor_woodsmoke/Wood_boilers.htm. [Last accessed: 27 Jan 2013].