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Low-cost measurement techniques to characterize the influence of home heating fuel on carbon monoxide in Navajo homes

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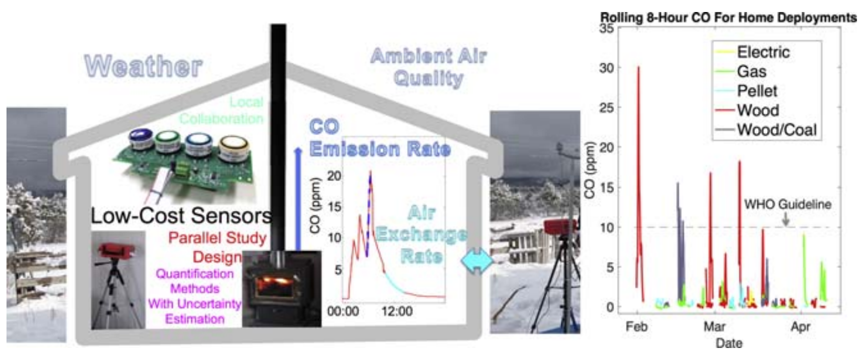
HIGHLIGHTS

- Heating with wood and coal has led to poor indoor air quality in some Navajo homes.
- Low-cost sensors enabled a study of indoor air quality and home heating fuel type.
- Concentrations of CO in some wood and coal heated homes exceeded health guidelines.
- A CO mass balance model was used to estimate ventilation and CO emission rates.
- Unhealthy indoor air quality was exacerbated by poor ventilation in some homes.

GRAPHICAL ABSTRACT



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ABSTRACT

A large fraction of the global population relies on the inefficient combustion of solid fuels for cooking and home heating, resulting in household exposure to combustion byproducts. In the southwestern United States, unhealthy air quality has been observed in some homes that use solid fuels as a primary source of heat on the Navajo Nation. In order to better understand how home heating fuel choice can influence indoor air quality in this region, we used recently developed low-cost electrochemical sensors to measure carbon monoxide (CO) air mole fractions continuously inside and outside 41 homes in two communities on the Navajo Nation. Using low-cost sensors in this study, which don't require extensive training to operate, enabled collaboration with local Diné College students and faculty in the planning and implementation of home deployments. Households used natural gas, propane, pellets, wood, and/or coal for heating. We developed quantification methods that included uncertainty estimation for Alphasense CO-B4 sensors, for measurements both inside and outside homes. CO concentrations elevated above background were observed in homes in each heating fuel group, but the highest hourly concentrations were observed in wood and coal burning homes, some of which exceeded World Health Organization Guidelines on both an hourly and eight-hourly basis. In order to probe the many factors that can influence indoor pollutant concentrations, we developed and implemented methods that employ CO emission and decay time periods observed in homes during everyday activities to estimate air exchange rates as well as CO emission rates on the basis of a given well-mixed volume of air. The air quality measurement tools and methods demonstrated in this study can be readily extended to indoor air quality studies in other communities around the world to inform how home heating and cooking practices are influencing indoor air quality during normal daily activities.

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1. Introduction and background information

Solid fuels are used by 3 billion people to cook and heat their homes in open fires or leaky stoves, leading to an estimated 4.3 million premature deaths each year associated with household air pollution from inefficient combustion of solid fuels (World Health Organization, 2016). It is estimated that 500,000–600,000 low-income individuals in the United States are potentially at risk from household air pollution from inefficient stoves used to burn solid fuels (Rogalsky et al., 2014).

1.1. Home heating on the Navajo Nation

On the high desert plateau of the southwestern United States, the majority of households on the Navajo Nation don't have access to natural gas in their homes, and since heating with propane or electricity is relatively expensive, many households choose to burn wood for home heating. Frequently households augment wood heating fuel with coal from one of three nearby coal mines. A common practice is to add coal to a fire late in the evening to help it burn through the night and into morning. Pellet stoves are also used in a small percentage of houses. One major drawback of using pellet stoves is that they often require reliable electricity to operate – a challenge in the region. Concern about the use of woodstoves on the Navajo Nation has been raised following the findings of several previous studies in which elevated particulate matter (PM) concentrations were observed in some wood and coal burning homes (Bunnell et al., 2010; Morris et al., 1990; Robin et al., 1996).

Switching from wood and/or coal to an alternative heating method like passive solar, electricity, natural gas, or propane when possible has been proposed as one way to mitigate exposure to solid fuel combustion byproducts in Navajo homes. Making improvements on existing stoves, like sealing leaks and or replacing flues, has also been proposed in addition to replacing older stoves outright with new Unites States Environmental Protection Agency (USEPA) certified models. Champion and colleagues designed and applied a framework based on culture, perceptions, and science in order to compare these potential solutions to mitigate pollution from solid fuel burning to the indoor environment. They found that replacing older stoves with new USEPA certified models is likely the most appropriate intervention (Champion et al., 2016). We designed the study presented here to offer information to Navajo Nation households about home heating practices and indoor air quality from another perspective. We measured carbon monoxide (CO) in homes using different fuels for heating to characterize how fuel choice can potentially impact CO concentrations in the indoor environment, which as a byproduct of incomplete combustion, could be accumulating in homes to unhealthy concentrations in connection with leaky heating appliances.

1.2. Home heating fuels and indoor air quality

A number of previous studies have shown differences in indoor air quality among homes grouped by the type of fuel each used for heating and cooking. Elevated CO concentrations in homes have often been observed in concert with elevated concentrations of other combustion byproducts. A study of homes in Berlin heated with coal, wood, or natural gas found that coal burning homes generally had higher concentrations of CO, sedimented dust material, heavy metals (inside the sedimented dust), and polycyclic aromatic hydrocarbons (PAHs) than homes heated with central forced air (Moriske et al., 1996). In Korea, homes and offices using supplementary kerosene heaters in winter months had higher CO, carbon dioxide (CO_2), nitrogen dioxide (NO_2), and a host of aromatic hydrocarbons, than homes and offices without kerosene heaters (Baek et al., 1997). One study in southwest China showed that average daily peak CO, PM_1, $PM_{2.5}$, and PM_{10} concentrations where higher in wood-burning homes than in coal-burning homes. These studies all show air quality differences (including CO concentrations) in homes connected to heating fuel groups, even though many other potentially important driving factors like air exchange rates, weather, ambient air quality, heating appliance type, operation practices and maintenance were not controlled for. In light of these previous findings, CO emissions from home heating and cooking appliances using different fuels could differentially contribute to unhealthy indoor air quality on the Navajo Nation.

1.3. CO exposure and public health

Acute exposure to CO can cause the formation of carboxyhemoglobin (COHb) in the blood, which inhibits oxygen intake (US Environmental Protection Agency, 2016). The accumulation of too much COHb in the blood, greater than 40%, can be lethal (Nelson, 2006). The percent of COHb that accumulates in blood depends on CO exposure in terms of concentration and duration (Varma et al., 2015). Chronic exposure to CO, to daily mean levels as low as 0.6–10.9 mg/m^3 (approximately 0.5–9.4 ppm) has been connected to increased risk of cardiovascular morbidity (World Health Organization, 2010). Exposure to 9 ppm of CO or more for longer than 8 h can lead to blood COHb levels of above 2.5% and possible health effects (Townsend and Maynard, 2002). Concerns have been cited about low-level CO exposure, as a common component of air pollution, in connection with possible neurodevelopmental impacts related to auditory systems and autism (Levy, 2015). In a study of ambient CO exposure in Wuhan, China, a 15% increase in premature births was observed per 100-μg/m^3 increases in mean CO concentrations during pregnancy in respective urban core districts (Qian et al., 2016).

1.4. Indoor CO emissions associated with home heating and cooking activities

The United States Environmental Protection Agency (US EPA) reports that average CO levels measured in homes without a gas stove range from 0.5–5 ppm and that levels near a well-tuned stove and a poorly tuned stove range from 5 to 15 ppm and 30 ppm or higher, respectively (US Environmental Protection Agency, 2016). A recent study of CO in 352 homes in California showed higher concentrations of CO in homes with unvented gas stoves and other vented gas appliances than in homes with just vented gas appliances. Peak hourly CO in homes with unvented gas stoves ranged from approximately 0 to 20 ppm (Mullen et al., 2016). CO levels in homes that use solid fuels like wood and coal for home heating have not been studied in the United States in recent years to our knowledge, though studies of elevated PM in homes on the Navajo Nation and elsewhere in the United States suggest there may be elevated levels of other combustion byproducts, like CO, in some of these solid fuel burning homes. A study in a rural Chinese village found peak hourly CO levels to range from 1.1 to 169 ppm in homes that heated and cooked with solid fuels (Fischer and Koshland, 2007).

1.5. Air exchange rates

Many homes are naturally ventilated leading to low air exchange rates and allowing emissions from combustion along with CO_2 among other bioeffluents from occupant respiration and metabolism to accumulate. The American Society for Heating Refrigeration and Air Conditioning Engineers (ASHRAE) defined fresh air requirements for ventilation of residential facilities to be 0.35 air changes per hour (ACH) for living areas (Beaton et al., 2004). Homes on the Navajo Nation are smaller on average than homes in other parts of the United States, with less than four rooms in 75% and 43% of rural and urban homes respectively (RPI Consulting, 2010). Proportionally more Navajo Nation homes are heated with wood and/or coal than in other parts of the United States. The increased potential for emissions of combustion byproducts from home heating and cooking appliances to the indoor