Modeling Pollution from

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Residential wood combustion emits significant quantities of health damaging air pollutants, including fine particulate matter ($PM_{2.5}$), carbon monoxide, and nitrogen oxides, along with known carcinogens, such as benzene and polycyclic aromatic hydrocarbons. According to the U.S. Environmental Protection Agency (EPA), $PM_{2.5}$ is the largest health threat from woodsmoke. Health damages associated with $PM_{2.5}$ exposure include respiratory and cardiac mortality, lung function decrements, exacerbation of lung disease, lung cancer, and developmental and immunological effects.

A large percentage of the general population is susceptible to adverse health impacts as a result of acute and chronic $PM_{2.5}$ exposure, including children, asthmatics, persons with respiratory or heart disease, diabetics, and the elderly. A recent review of studies[1] concluded that there was insufficient evidence to suggest that woodsmoke PM is any less harmful than other types of PM.

Relative to oil- and gas-fired furnaces, most conventional wood-burning devices used for residential space and water heating are large emitters of $PM_{2.5}$ pollution. In terms of total $PM_{2.5}$ mass emitted over time (e.g., grams per hour, g/hr), woodstoves meeting EPA certification limits still emit over 85 times more $PM_{2.5}$ than an oil or gas furnaces, while conventional woodstoves emit over 250 times more $PM_{2.5}$.[2] Higher performing wood-burning devices are feasible and used in Europe, but are not yet commonplace in North America.

Of special note is the rising prevalence of outdoor wood boilers (OWBs) used to provide residential and commercial heating. An OWB is a wood-fired furnace typically housed within a small insulated shed located some distance from a house or building, and designed to burn a large amount of wood over long periods of time. Sales of OWBs in the United States increased nearly ten-fold from 1999 to 2007 (from approximately 4,800 to 45,000 OWB sales per year). Based on $PM_{2.5}$ emissions testing, unregulated OWBs emit almost 4 times more

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$PM_{2.5}$ than conventional wood stoves, 12 times more than EPA-certified wood stoves, 1,000 times more than oil furnaces, and 1,800 times more than natural gas furnaces.[2]

One potential driver for the increasing popularity of wood combustion is the price volatility of heating oil and natural gas. For example, in the northeastern United States, where heating oil is relatively more common than elsewhere in the United States, heating oil prices doubled from 2006 to 2008, before returning to 2006 prices in November 2009.[3]

Concern over domestic energy security and climate change are additional drivers for increasing interest in wood use, and biomass in general. Community-scale advanced wood combustion approaches have been argued to have a role in addressing these issues,[4] but the sustainable use of biomass is the subject of much debate.[5,6]

Regulatory Status

Provincial, state, and federal agencies have adopted a number of approaches to address woodsmoke pollution. In Canada, residential wood-burning has been identified as a priority sector for the reduction of contaminant emissions under the Canada-wide standards for $PM_{2.5}$ and ozone. In pursuing measures to achieve the Canada-wide standards, the Canadian Council of Ministers of the Environment (the association of environment ministers from the federal, provincial, and territorial governments) agreed in 2000 to participate in new initiatives to update the Canadian Standards Association (CSA) standards for new wood-burning appliances; develop a national regulation for new, clean-burning residential wood-heating appliances; pursue national public education programs; and assess the option of a national wood stove upgrade or change-out program. The CSA is expected to propose an updated standard for wood-heating appliances in spring 2010 that would lower the PM emission rate to 4.5 g/hr for noncatalytic wood-heating appliances, and to 2.5 g/hr for catalytic wood-heating appliances.[7]

In the United States, EPA established a New Source Performance Standard (NSPS) for residential wood stoves under the U.S. Clean Air Act (CAA) in 1988. While the CAA requires an NSPS to be reviewed every eight years, the wood stove NSPS has remained unchanged for the past 20 years, despite advances in wood combustion technologies. In addition to not reflecting current best technologies, the wood stove NSPS does not cover devices in use prior to implementation of the rule, nor does it encompass several increasingly popular residential wood-burning devices, including fireplaces, masonry heaters, pellet stoves and indoor and outdoor wood boilers, furnaces, and heaters. In recognition of this, EPA initiated in 2008 a review of technical information that could lead to a revised and expanded suite of emission standards for wood combustion devices.

EPA currently has a voluntary certification program for manufacturers of OWBs to promote the production and sale of cleaner more efficient models. At EPA's most stringent certification level (Phase 2), certified OWBs are approximately 90% cleaner than uncertified models. However, even OWBs qualifying for Phase 2 certification still emit one to two orders of magnitude more $PM_{2.5}$ on an annual average emission rate basis than residential oil or gas furnaces.[8]

In addition to regulatory standards, air quality agencies are implementing new or enhancing existing wood stove change-out programs. While change-out programs provide improvements over existing technologies, the newer change-out replacement devices may not necessarily be the cleanest available in the marketplace absent an accompanying emission standard based on current best technologies. As the replacement stoves installed under the change-out programs will be in use for years to come, these programs may in fact be lost opportunities for installing the cleanest available wood-burning devices.

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Ambient Woodsmoke Concentrations

With the rising popularity of wood combustion, a key problem in assessing associated air pollution is that topography, such as enclosed valleys, can create significant woodsmoke spatial variability, including "hotspots." Regulatory air pollution monitoring networks are typically not dense enough, particularly outside of urban areas, to capture fully this spatial variability. In addition, there is an accompanying lack of sufficiently detailed information on the location and activity levels of wood-burning appliances.

The high emissions from wood combustion relative to other heating fuels can lead to large contributions of woodsmoke to ambient $PM_{2.5}$ levels, especially during the heating season. In the United States, residential wood combustion (RWC) is responsible for 6.9% of the national primary $PM_{2.5}$ emissions, which is greater than the contribution of on-road (2.5%) and similar to that for off-road (7.3%) mobile sources.[9] Emissions contributions from RWC vary across the continent and are known to be higher in the Northeast[10] and Canada.

Source apportionment studies suggest 20–30% contributions from wood combustion to ambient PM levels, although this estimate varies by location.[11] For example, RWC is the largest contributor to $PM_{2.5}$ in rural areas of Montana[8] and New York State,[12] as well as in Seattle,[13] but it also accounts for 15% of $PM_{2.5}$ in the Southeast United States.[14]

Given the seasonal nature of wood combustion and its prominence in nonurban areas, RWC is usually not well-characterized by regulatory monitoring networks. For example, in 2008 there were 29 ambient air monitoring stations in New York State, reporting $PM_{2.5}$ measurements for regulatory purposes, or one monitor per 1,628 square miles. Since monitors are generally concentrated in urban and suburban settings (17 of the 29 New York State monitors are located in the New York City metropolitan area), coverage can be sparse across large parts of a state. Alternative approaches that focus on smaller communities, especially during the heating season, are needed.

Modeling

Because the contribution of wood combustion to PM concentrations can be relatively high, there is increasing need to identify hotspots and to understand spatial patterns of pollutant concentrations. In areas of the Pacific Northwest, a collaborative effort with Professor Tim Larson of the University of Washington resulted in a modeling approach that combined geographic and demographic information with mobile monitoring to characterize the levels and spatial variability of woodsmoke.[15-17] These models have subsequently been used to estimate exposure in epidemiological studies.[18,19]

The approach relies on the understanding that the highest woodsmoke concentrations occur on cold nights when wind speeds and dispersion are low. Under these conditions, smoke transport is dominated by drainage flow such that smoke pools in valleys and other low-lying areas. Using fastresponse nephelometers coupled with a global positioning system logger, mobile monitoring can investigate these areas to map spatial woodsmoke gradients. To identify potential hotspots, the approach first uses emissions inventories and wood appliance survey data combined with property assessment records to spatially map areas of high and low emissions. With this estimated emissions map, a mobile monitoring route is designed to traverse areas of both high and low expected concentrations, and optimally locate fixed monitors to more accurately measure concentrations of $PM_{2.5}$ and woodsmoke markers, such as levoglucosan (an organic compound formed by cellulose combustion).

The mobile monitoring data provide a rich amount of information regarding the spatial patterns of fine particle concentrations. By collecting these measurements during nighttime, and especially during periods of cold temperature and low wind speeds, the impact of other sources such as vehicle exhaust are minimized while maximizing the ability to measure woodsmoke. The mobile monitoring data can indicate the presence of high short-term average concentrations of woodsmoke in specific areas. Further, the mobile monitoring data can be linked to geographic and demographic predictors to model spatial patterns of woodsmoke concentrations, so that one can estimate concentrations at high spatial resolution throughout an airshed.

Unlike land use regression models for traffic-related pollutants that characterize predictors in a circular region around measurement sites,[20] or dispersion models that estimate concentrations as a function of source-receptor distance, the spatial woodsmoke model described here utilizes hydrological catchment areas to characterize sources in upslope areas that may contribute to a measurement at a downslope point. In the Pacific Northwest, this approach successfully modeled woodsmoke at a resolution of 100 m and found that emissions and demographic variables are useful predictors of measured concentrations. Measurements of levoglucosan or other biomass combustion markers from fixed monitoring sites indicate a high correlation with these modeled concentrations, supporting the application of this approach to mapping woodsmoke.

The spatial mapping approach has since been enhanced and extended to more rural areas. In one example, in small communities in northern British Columbia, it was feasible to simply collect mobile measurements on every road in the community to map concentrations.[21] Similar applications have been used by regulatory agencies and health authorities to assess community smoke issues (e.g., resulting from open burning[22]). More recently, we have applied the mapping approach in the northeastern United States, where woodsmoke emissions are thought to be greatest. In this application, we used U.S. Census data on heating fuels, combined with available survey data on proportions of different combustion appliances. These data were then spatially allocated within census block groups using property tax assessment data, which include information on fireplaces. As in previous applications, this initial predicted emissions map was used to design a mobile monitoring campaign and to optimally locate a series of fixed monitors throughout a study region in New York's Adirondack Mountains.[23]

A significant enhancement in this application was the use of a two-channel aethalometer in combination with a nephelometer. The two-channel aethalometer provides semi-quantitative real-time measurements of woodsmoke.[24] Results indicate that aethalometer peaks coincide with nephelometer measurements, supporting the use of nephelometer data in this method as an indicator of woodsmoke. As in the Pacific Northwest, monitoring data were used in the hydrological catchment areas approach to develop a spatial model for both the specific region where the mobile monitoring was conducted, as well as a larger seven-county region. This larger screening model was evaluated with a more limited monitoring program. By combining the model with population data, it was estimated that roughly 25% of the region's population lives in areas with the highest concentrations of woodsmoke.

Summary and Conclusions

With increasing interest and growth in wood combustion, exposure to elevated woodsmoke levels is an emerging public health concern. This is particularly salient in nonurban areas, especially in complex terrains where pollution dispersion in valleys can be low. Monitoring networks typically are not dense enough to capture woodsmoke spatial patterns and potential local hotspots. To address this, we have described a modeling approach that can be used as a screening level assessment to identify areas of potential concern.

Because the model uses publicly available information sources (e.g., census, property assessment, and survey data), it has potentially broad application for the assessment of population exposure to woodsmoke where extensive ambient monitoring networks are lacking. The modeling approach has now been successfully applied in the Pacific Northwest (Washington and British Columbia) and the Adirondacks region of New York State, demonstrating it is readily transferable across regions. However, regionally specific woodsmoke emissions and monitoring information can help improve the modeled woodsmoke spatial patterns.

For public health decision-makers, the modeling technique can provide a tool to help prioritize where to locate fixed monitoring sites and mobile monitoring routes for targeted field campaigns that best reflect where public exposure and woodsmoke levels may be highest. As another application, the modeling technique can also help identify high woodsmoke locations for targeted woodstove change-out programs or other strategies. These examples illustrate the modeling approach's potential to provide a flexible and broadly applicable tool that can help guide limited resources towards reducing public exposure to health damaging woodsmoke levels. **em**

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