Locating and Quantifying Fine Particle Matter Emissions Originated from Residential Wood Burning

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ABSTRACT

We investigate methods for quantifying and locating the levels of fine particulate matter (PM2.5) originating from residential wood combustion and emitted to the atmosphere. Physiographic and demographic data were compiled and processed within a Geographic Information System to spatially relate residential wood burning activity potential. A survey conducted through face-to-face and telephone interviews over several regions in California were employed to examine the research results.

INTRODUCTION

Residential wood combustion (RWC) contributes to the ambient concentration of fine (PM2.5) particulate matter and volatile organic compounds (VOCs) [McDonald J. D. et al. 2000; Benner, et al., 1995]. Air pollution generated from residential fireplaces and wood stoves remains inadequately addressed in most areas [Diem and Comrie, 2001]. Yet this is one source of air pollution that produces fine particles and gases containing a multitude of toxic substances and carcinogens that are often associated with morbidity and mortality in populated regions [Purvis and McCrillis, 2000]. In order to estimate levels of fine particulate matter (PM2.5) in the atmosphere caused from residential wood burning, it is necessary to have well defined information about where emission sources are located [Dasch, 1982]. Currently, the spatial information associated with area source emissions such as residential wood burning is rudimentary at best. Statistics are not kept on the capability or use of wood burning devices in residential households. There is an urgent need for a standard method of predicting and accounting for the amount and location of fuels being consumed by residential wood burning activities. Furthermore, predicting seasonal variation will provide improved emission estimates temporally and spatially.

It is reasonable to hypothesize that residential wood burning practices might be associated with certain demographics, the location of the residence, the characteristics of the neighborhood and surrounds, access to fuels, or several other household characteristics. In this study, we develop a consistent way of mapping residential wood burning potential in a spatial and temporal manner by using consistent and well-documented household density characteristics and their location. Using geographic information systems (GIS), demographic data from the US census, sources and location of wood fuel, and data collected from face-to-face and telephone interviews are integrated with information on climate zones, elevation, the distribution of fire appliances and household densities where wood burning is actively used as a heating source; in order to produce estimates of potential wood burning activity.

Our research results help to better understand where and how much residential wood burning is contributing to air quality. With this knowledge we can identify regions and times of concern, and better plan mitigation strategies to improve air quality.

EXPERIMENTAL METHODS

Study Site Determination

Our objective in this study is to begin to understand residential wood burning habits and locate where it is occurring in the state of California. We begin by choosing a sample site that best describes the variety of California yet allows us to keep within our modest budget for the study. We choose a study site of 28 counties that span from the San Francisco Bay Area eastward to almost the Nevada border (Figure 1).

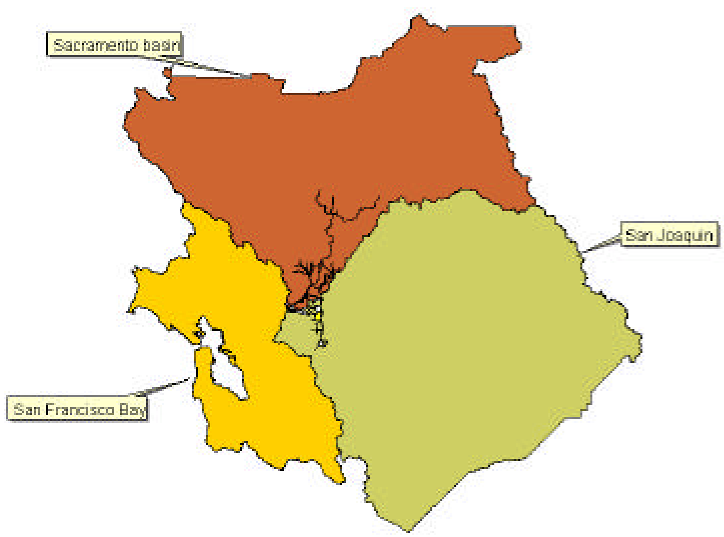

Figure 1 Study site in San Francisco Bay Area

This region represents a good cross-section of California as it is characterized by multiple land uses, contains a good proportion of coastal and inland physiography, represents a wide distribution of the state's demographics, and has a diverse climate typical of the rest of California. The study site essentially bounds three California regions known as the Sacramento Valley, the San Joaquin Valley and the San Francisco Bay Area.

Demographic Characteristics

Demographic data for the State of California is obtained from the U.S. 1990 Census where tract, block group and block data are used to identify and characterize regions of residential wood burning activity. Some additional information on neighborhood infrastructure to determine urbanization and access to fuels and facilities are acquired from the US Geological Survey (USGS) and the US Forest Service (USFS). Characteristics of these demographics cover categories of population, housing, facilities, infrastructure, and socio-economic factors. (Table1). Due to the wide range of census tract area (they vary from 0.0002 km^2 to 2500 km^2) and to generate independent variables, which characterize neighborhoods, we standardized demographic features by normalizing variables by population or area in each tract. We normalize other variables by household as residential wood burning occurs and is surveyed at the household level.

Table 1 Normalization rules for individual variable

Normalized by population	Normalized by households	Normalized by area
Ethnicity	Family Type	Population
Age	Household Income	Households
Marital Status	Housing occupants	Road
Persons in Institutions	Housing Value	Bridges
Migratory Status	Housing Contract Rent	Parks
Type of Commute	Housing in Structure	Facilities
Student Population	Housing Water, sewage	
Educational Attainment	Housing age	
Employment Status	Source of Heat in Housing	
Occupation	Vehicles in Household	

One of the attributes in the variable *"Source of Heat in Housing"* is *"Coalwood"*. The values here represent the number of households (in the census region) using coal or wood as their primary heating source. Since no California household has used coal as a source of fuel in the past 20 years, the data records reported here are about using wood fuel.

Spatial Feature Compilation

Besides the use of demographic data to help predict residential wood burning activity, we identify and incorporate several location variables, which are reasonable to hypothesize influence of residential wood burning activity. These include elevation, climatic zones, accessibility to forests (natural fuel source), and whether the residence is in urban, suburb or rural territory.

The elevation data was obtained from the USGS at the scale of 1:250,000 (a resolution of approximately 83×83 m^2). Climate data was obtained in the form of *climatic zones* provided by the California Energy Commission and represented as an average value over ten years. We adopt their concept of heating-degree-days (HDD), which is the number of degrees that the average daily temperature is below 65 °F. We extract and assemble data on forests (potential wood-fuel source) from a joint *land cover* exercise (30×30 m^2 resolution) between the USGS and Environmental Protection Agency (EPA). We define accessibility to forest fuel-wood as the availability of forest within a driving distance of 30 miles.

It is reasonable to assume that restrictions, either political or social, would influence the practice of residential wood burning so we classify regions as urban, suburban or rural. We alter the traditional definition of urban, suburb and rural [Nelson, 1992], based solely on population density by enhancing it with information on household density and road density (aggregated as road length / km^2).

Statistical Analysis

To identify important independent variables that could be used to predict residential wood burning, a stepwise linear regression analysis is conducted. We use the demographic and location data in the selection of independent variables to predict the number of households using wood as their primary heating source, the dependent variable. The statistical analysis is conducted on four scenarios: 1) using all available data, 2) using all available data except elevation (DEM), 3) excluding both DEM and forest accessibility, and 4) replacing the urban, suburb and rural (URS) classification with an urban/non-urban (UR) classification. The first two scenarios test for the better predictor between DEM and forest accessibility, while the last two scenarios determine if further classification of non-urban to suburb and rural is necessary to improve the predictions of residential wood burning activity. The variables of both DEM and forest accessibility are not included in the final two scenarios.

Survey Design and Sampling Strategy

A survey conducted through face-to-face and telephone interviews is employed to collect quantitative information on demographics, distribution of fire appliances, and wood burning activity; and to validate the results of our statistical analysis. The questionnaire has a special section for acquiring records on demographics, flowed by sections for acquiring information on fireplaces, woodstoves, fireplace inserts, and other wood burning appliances. Within each section, a question on the number of burning events during the year is incorporated to identify wood as primary heating source.

Due to the large variation in household density over our entire study site, a stratified random sampling technique is employed to generate locations (households) to be surveyed. The stratification is based on regions of urban, suburb and rural where a sample point data set is generated as a map layer. The physical location of residents to be interviewed is extracted by overlaying the generated sample point set with a map of street information. We generate 3076 sample points for the entire region and attempt 9228 surveys to reach a goal of three different households per sample point.

RESULT AND DISCUSSION

Influence of Spatial Features

The results in Table 2 demonstrate that potential residential wood burning is predictable. Spatial variables such as elevation, forest accessibility, and factors of urban, rural and suburb are identified as significant predictors. Among these variables, elevation seems to have the most influence for potential wood burning activity. Cold and windy climates at high elevations generate demand for heating. In addition, most of the forests (a potential source of fuel) are located in the mountainous regions. Casual observation of wood fuel sales reveals supermarkets in the Lake Tahoe region report more wood fuel sold than their SF Bay Area counterparts. Lake Tahoe locates on the board between California and Nevada states and its average surface elevation is 6,225 feet above sea level (3,500 -10,400). It is a famous skiing area. This phenomenon matches well with the elevation impact results on wood burning. Without considering correlation effects, equation (1) below explains approximately 86% of the variation with 9 variables listed in the first column in Table 2.

$$AP = 3069 + 2.342 \times DEM + 412.75 \times URS + 102.96 \times RETI + 30 \times FORACC - 45 \times OCCUPIED + 126.6 \times FARM\_INC - 23.5 \times AGEGT55 \quad (1)$$

Table 2 Predictors identified for estimating wood burning activity potentials

All variables		No DEM		No-dem-foracc		URS->UR	
Vars	Adjut. R^2	Vars	Adjut. R^2	Vars	Adjut. R^2	Vars	Adjut. R^2
DEM	.645	FORACC	.564	URS	.386	UR	.378
URS	.782	URS	.755	RETI_INC	.547	OCCUPIED	.538
RETI_INC	.808	OCCUPIED	.793	OCCUPIED	.614	RETI_INC	.620
FORACC	.824	DETACHED	.812	FOR_DIST	.651	AGE35_54	.651
OCCUPIED	.833	AVE_RNT	.828	MON_12	.688	GRADUATE	.676
FARM_INC	.846	AGE35_54	.843	APPL_TYP2	.707	APPL_TYP2	.694
AGEGT55	.854	MON_2	.847	DETACHED	.722	FOR_DIST	.707
AGE35_54	.857	MON_12	.852	-	-	MON_2	.723
OWNR_OCC	.863	-	-	-	-	-	-

Next to elevation, forest accessibility explains approximately 56% variation of residential wood burning activity potential as described in the third and fourth columns of Table 2. However, there is a high correlation between elevation and forest accessibility (shown in Table 3) so we can eliminate forest accessibility as an independent variable. Equation (2) excludes forest accessibility and is still able to explain approximately 83% of the variation on residential wood burning practices.

$$AP = 1328 + 3.87 \times DEM + 489.5 \times URS + 126.4 \times RETI - 25 \times AGEGT55 + 100 \times FARM\_INC - 32.5 \times OCCUPIED + 18.2 \times AGEGT35\_55 \quad (2)$$

Table 3 Correlations between variables of spatial and demographical features

	URS	AGE35_54	OWNR_OCC	**WOOD**	HDD	FORACC	DEM
URS	1	-.024	.331	.623	.176	.267	.343
ZAGE35_54	-	1	.444	.107	.140	.122	.198
OWNR_OCC	-	-	1	.391	.107	.281	.360
WOOD	-	-	-	1	.393	.752	.804
ANNU_HDD	-	-	-	-	1	.329	.524
FORACC	-	-	-	-		1	.835
DEM	-	-	-	-		-	1

The mean monthly temperature is important after eliminating the elevation factor from the analysis [Sexton et al., 1985]. This implies that potential residential wood burning activity is influenced by climate. The high correlation between elevation, HDD and forest accessibility, renders heating-degree-days insignificant when elevation and forest accessibility variables are included.

We also discover that there is no advantage in dividing non-urban classified regions into suburb and rural. The last four columns in Table 2 are the results for the scenarios on UR and URS and indicate suburban and rural have no clear distinction of wood burning practices.

Impacts of Demographical Characteristics

Several demographic characteristics are directly related to wood burning practices: proportions of retired income (RETI_INC), ratio of occupied houses, farm income in households (FARM_INC), age groups of residents (AGE > 55 or 34<AGE < 54), and owner occupied units (OWNR_OCC). The contributions to the predictive model using the selected demographic variables in each scenario are consistent. Retired people require more economic heat energy. Farm households have better accessibility to wood fuels. Occupied units are an obvious factor since likely only occupants need heat energy. Residents whose ages range between 35 or 54 are more likely to have small children, have pressures of income, and are more likely to look to more cost effective fuels.

Validation

We validate the linear regression analysis results with data collected through interviewing residents in the three study regions. The validation is conducted for five circumstances: 1) urban, non-urban and both, 2) individual counties, 3) climatic zones, 4) terrain elevation classes, and 5) the distance to the nearest edge of the forest.

Comparisons between model prediction and surveyed data on percentages of households burning wood as primary heating source is analyzed separately for urban, non-urban and all areas in the study site. The model prediction matched survey data at almost all circumstances as shown in Table 4. The primary wood burner in surveyed data was defined as greater than 90 events per year.

Table 4 Percentages of households burning wood as heating source

	Rural/Surburb		Urban		Urban and non-urban	
	Survey	Model	Survey	Model	Survey	Model
Sacramento Basin	12.94%	24.34%	5.45%	1.96%	9.56%	14.14%
San Francisco Bay	5.00%	10.06%	4.57%	1.17%	5.16%	2.72%
San Joaquin	10.93%	21.90%	6.67%	2.48%	10.09%	17.83%
Correlation	0.996		0.978		0.990	

Sixteen counties where we have sufficient survey points are included to validate the model prediction for potential residential wood burning. The percentages of serious wood burning households in each county are listed in Table 5. The predicted and surveyed percentages of wood burning activities for individual counties are highly correlated (0.82) and the model could explained 67% of the variations in the survey data.

Table 5 Percentage of wood burning households from survey and model prediction at county level

County	Survey	Model
Alameda	7%	1.45%
Merced	19%	11.39%
Nevada	29%	37.79%
Placer	20%	24.75%
Sacramento	5%	2.02%
San Joaquin	12%	9.04%
Stanislaus	6%	10.06%
Calaveras	17%	39.44%
Contra Costa	3%	2.83%
Marin	0%	6.45%
San Mateo	4%	6.11%
Santa Clara	4%	0.96%
Solano	8%	10.37%
Sonoma	8%	10.42%
Sutter	5%	8.61%
Yolo	8%	6.39%

There are six different climatic zones within the study area and the mean heating-degree-days (HDD) among these climatic zones vary from 2643 to 5532. The model predicated and surveyed ratios of wood burning households for each climatic zone have a correlation coefficient of 0.786 (Table 6). The correlation between predicted and surveyed wood burning ratios from the survey is at 0.786. The correlation between HDD and predictions is 0.956, between HDD and surveyed is 0.594, and the prediction to surveyed data achieved an R^2 value of 65%.

Table 6 Model predicted and surveyed ratios of wood burning households in individual climatic zones

Climate zones	Model	Survey	HDD
2	10.28%	2.78%	3026
3	2.85%	4.17%	2840
4	0.96%	3.92%	2643
11	23.32%	16.67%	2847
12	10.73%	8.24%	2697
16	71.59%	16.67%	5532

The study site can be naturally classified into five categories of DEM using the classification rules specified in Table 7. The correlation between surveyed and predicted ratios of wood burning households for each DEM class is 0.77. From the results of earlier linear regression analysis we discover that elevation is the most important factor in predicting potential wood burning activity and this validation confirms the effects of elevation on our objectives.

Table 7 Model predicted and surveyed the ratios of wood burning households for five DEM categories

DEM classes	Class rules	Model	Survey
1	< 77	4.22%	31.88%
2	< 244	11.81%	34.26%
3	< 488	30.81%	28.13%
4	< 798	38.22%	36.11%
5	rest (<1694)	59.48%	75.00%

Validation with distance to forest is not as successful. The correlation between predicted and surveyed is only 0.013. Because of this poor result, we developed a new way of assessing the impacts of forest on wood burning practices, by using forest accessibility described in the section of experimental methods. This advanced method improved our validation results enormously.

Table 8 Validation of prediction with distances to forest

Distant classes	Pts > 90	All pts	Model	Survey
1	115	327	19.70%	35.17%
2	66	201	2.35%	32.84%
3	55	150	5.52%	36.67%
4	20	90	11.42%	22.22%
5	28	105	6.55%	26.67%

CONCLUSION

Potential residential wood burning activity, for the most part is, is related to location. Elevation, accessibility to forest, and urban/non-urban are important variables in modeling the ratio of households that potentially burn wood as their primary source of heat. Our linear regression model identified several demographic characteristics related residential wood burning potentials. These demographic characteristics are complementary to location features in the modeling exercises.

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