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Model development for spatial variation of $PM_{2.5}$ emissions from residential wood burning

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Abstract

This paper presents a preliminary research result of spatially quantifying and allocating the potential activity of residential wood burning (RWB) by using demographic, hypsographic, climatic and topographic information as independent variables. We also introduce the method for calculating $PM_{2.5}$ emission from residential wood combustion with the potential activity as primary variable. A linear regression model was generated to describe spatial and temporal distribution of the potential activity of wood burning as primary heating source. In order to improve the estimation, the classifications of urban, suburban and rural were redefined to meet the specifications of this application. Also, a unique way of defining forest accessibility is found useful in estimating the activity potential of RWB. The results suggest that the potential activity of wood burning is mostly determined by elevation of a location, forest accessibility, urban/non-urban position, climatic conditions and several demographic variables. The analysis results were validated using survey data collected through face-to-face and telephone interviews over the study area in central California. The linear regression model can explain approximately 86% of the variation of surveyed wood burning activity potential. The total $PM_{2.5}$ emitted from woodstoves and fireplaces is analyzed for the study region at county level.

Keywords: Residential wood burning; Emission; Anthropogenic fine particle pollution; 1990 census; Fire appliances; Demographic characteristics

1. Introduction

Anthropogenic fine particles in the range of $<2.5\,\mu m$ ($PM_{2.5}$) and volatile organic compounds (VOCs) have been proven to have a major impact on human health (Browning et al., 1990; Cooper, 1980) and are often associated with morbidity and mortality (Querol et al., 2001). Residential wood burning (RWB) contributes to the ambient concentration of $PM_{2.5}$ and VOCs (McDonald et al., 2000; Lewis et al., 1988), and contains a multitude of toxic substances and carcinogens (Purvis and McCrillis, 2000). Although impacts of RWB on environmental air quality has drawn attention from scientists for more than two decades (Dasch, 1982), many issues remain inadequately addressed in most areas (Diem and Comrie, 2001). It is essential to construct a systematic method for estimating $PM_{2.5}$ emission from RWB. Such model would be helpful in mitigation management against atmospheric degradation.

Current methods of estimating $PM_{2.5}$ from RWC are for the most part based on survey data (Houck et al., 2001). Using survey method is costly when sampling large areas and the surveyed results can rapidly become outdated as demographics change (Healey and Ilbery, 1990). Hildemann et al. (1993) performed an analysis of urban organic aerosol using mathematic modeling. A similar standard method of predicting and accounting

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for the amount and location of fuels being consumed in RWC associated with the population dynamics is needed.

Many criteria, such as the number of households burning wood as a heating source, the duration of average burning event, the combustion efficiency of fire appliances, and the emission rate of fuel-wood type can affect the levels of $PM_{2.5}$ in the atmosphere caused by RWC. At any given time and location, the number of households with wood-burning activity can vary due to climatic conditions influenced by local environment and topography. We define the activity-potential of RWC as the number of households with burning activity in a year. Although the activity-potential can characterize households using wood burning for both primary and aesthetic heating purposes, primary heating dominates $PM_{2.5}$ emission of RWC in California and Oregon (Houck and Tiegs, 1998). We deal with primary wood burning only in this study.

This paper presents a modeling method for quantifying and spatially allocating activity-potential of RWB to improve estimation of $PM_{2.5}$ emissions into the atmosphere. The method involves two processes, illustrated in Fig. 1. The first process is linear regression for modeling the spatial distribution of activity-potential of RWC as a function of demographic and physical environmental data, which are gathered from both existing databases and surveys within the study area. The second modeling process we employ estimates the total $PM_{2.5}$ emitted from woodstoves and fireplaces in the study region using the activity-potential of RWB as the key variable. This variable determines the variation of emissions in space and time. A model was developed based on a hypothesis that RWB practices are associated with certain demographics, residential locations, access to fuels, and other household and neighborhood characteristics. The process was validated with the data compiled from face-to-face and telephone interviews over several regions in California. The study was conducted by using ArcView GIS and the method can be extended to study an inventory of allocating anthropogenic pollutant emissions from other sources requiring atmospheric management as studied by Diem and Comrie (2001), such as road dust pollution generated by vehicles and cigarette smoke.

2. GIS data for allocating $PM_{2.5}$ emissions

2.1. The study site

The chosen study site includes 28 counties ranging from the San Francisco Bay area to the Sacramento and San Joaquin valleys in the State of California. The site is located in the center of California, with latitude ranging

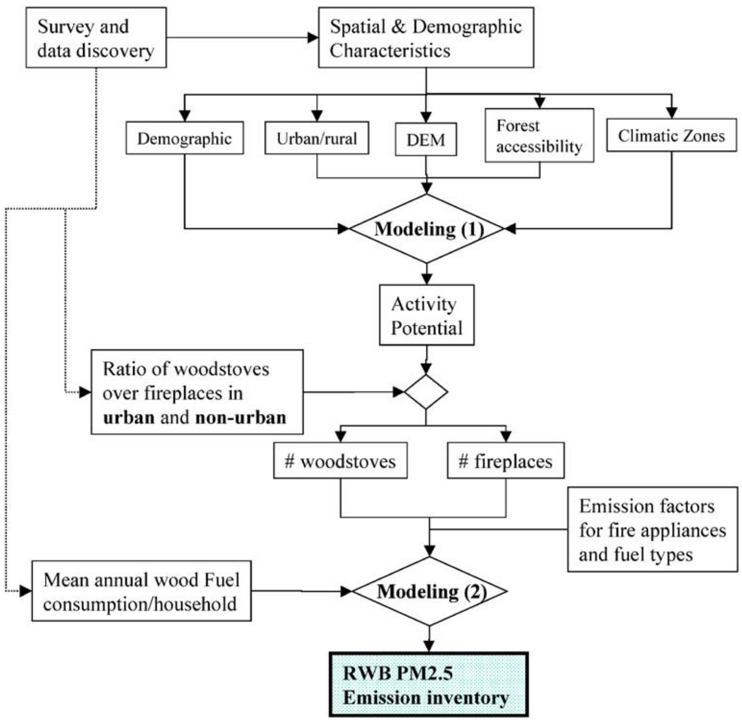

Fig. 1. Overview of the project of estimating $PM_{2.5}$ emission from residential wood combustion. The top part of the diagram highlighted is the research focus of this article.

from 37° to 39°N and longitude ranging from 121° to 123°W. Because of population and industry densities, air quality is a problem in the study area. The site also contains a good proportion of coastal and inland hypsography and is well represented with a mixture of urban and rural environs. The rural area of the region is characterized by multiple land uses, with about 30% being forested areas or national parks that supply wood-fuel.

2.2. Demographic characteristics

It has suggested that the ratio of households using wood-fuel as a primary heating source is likely influenced by demographic factors. However, there was insufficient information to confirm this conjecture and to identify specific demographic features critical in the prediction of wood burning activity-potential. We obtained demographic information from the US Census Bureau 1990 database to support these conjectures. From these data, we were able to characterize households and group them by census tract, an adequate spatial partition for our regional scale objective. Amongst the many independent variables in the census, we observed evidence of RWB, our dependent variable. Although this variable is reported nationally as the number of households using coal or wood as their primary heating fuel, in California where coal is unavailable, it represents wood burning. Due to the wide range of census tract area in our study site, we normalized RWB and reported it as a density value for each census tract.

2.3. Environmental characteristics

Temperature and climatic conditions in general provide the need for heating, while neighborhood characteristics and accessibility to fuel likely influence the heating source used. We obtained climate data in the form of climatic zones provided by the California Energy Commission and represented it as an average value over 10 years. We adopted the concept of heating-degree-days (HDD) or the number of degree-days where the average daily temperature is below 65°F, and heating is likely to occur. These HDD are more likely to occur at higher elevations where recorded temperatures are consistently lower in value. The elevation for the study area was obtained from the USGS as a digital elevation model (DEM) with a scale of 1:250,000, which was adequate for our regional scope. After processing and projecting it to a common Albers equal area projection, the resultant DEM grid has a resolution of approximately $83 \times 83\,\mathrm{m}^2$ per grid cell.

2.4. Accessibility to fuel-wood

RWB is more likely to occur in regions where fuel-wood is accessible. Since the majority of wood-fuel sale originates, either directly or indirectly, from the sites maintained by the US Forest Service, we sought to discover how RWB activity was related to accessibility to forest fuel-wood supply. Using data from the USGS National Land Cover Data (NLCD), we selected the attribute "Forested Upland" to represent forestland cover. Of the wood that was cut and burned, approximately 70% of RWB energy was either directly or indirectly obtained from sites where fuel-wood came from the Forest Service. The other 30% of fuel-wood came from private industrial timberland and ranch orchards. Accessibility to forest wood-fuel is calculated and compared using the radius distance from residents to the nearest forest boundary, and the percentage of forested areas within a specified radius distance (about 30 mile radius in our study).

2.5. Redefinition of urban and non-urban

The use of wood heating appliances is likely affected by the availability of alternative heating infrastructures such as gas and electricity. These utilities, for the most part, are heavily concentrated in urban regions where demand is high and the distribution of other utilities, such as road networks, are well developed. Although the US Census provides a classification of urban, suburban and rural, it is based solely on population density (Nelson, 1992). This classification system can be misleading in analyzing RWB when considering neighborhood impacts of airborne activity.

We calculated urban areas by enhancing population density (people/km^2) with factors including road density (aggregated road length/km^2) and house density (houses/km^2). When the calculation was applied to the 1990 US Census data, we eliminated the misclassification of territories such as parks, industrial and commercial lands, and other open areas in urban centers. The classification of urban, suburban and rural is conducted as:

$$A_i(r,p,h) \subseteq U_\mathrm{b} \quad \text{if } [\forall r \in \{>10{,}000\,\mathrm{m/km^2}\} \cup \forall p \in \{>1000\,\text{people/km}^2\} \cup \forall h \in \{>400\,\text{houses/km}^2\}], \tag{1}$$

$$A_i(r,p,h) \subseteq R_\mathrm{u} \text{ if } [\forall r \in \{<3500\,\mathrm{m/km^2}\} \cap \forall p \in \{>100\,\text{people/km}^2\} \cap \quad \forall h \in \{>60\,\text{houses/km}^2\}], \tag{2}$$

$$A_i(r,p,h) \subseteq S_\mathrm{u} = R_\mathrm{u} \cup U_\mathrm{b}, \tag{3}$$

where $A_i(r,p,h)$ is any unit area and is a function of r, p, and h. The r stands for the mean road density in the area of $A_i(r,p,h)$, p is the population density, and h is the house density. U_b is the set of urban areas, S_u is the set for suburban and R_u is the set for rural.

3. Quantitative analysis

Based on our initial concepts, a stepwise linear regression analysis was conducted to quantitatively verify the method. The candidate independent variables for the statistical analysis included demographic characteristics, elevation, climatic zones, location of urban, suburban and rural areas, and generated information on accessibility to forest fuel-wood. Both forest accessibility and radius distance to the nearest forest edge were included as independent variables. The dependent variable, the number of households using wood as primary heating source, was obtained from the 1990 census data.

3.1. Influence of spatial features

The statistical analysis results demonstrate that spatial variables such as elevation, forest accessibility, and classification of urban, rural or suburban are good predictors. Among these variables, elevation is most influential since cold and windy climates at high elevations generate demand for heating. This quantitative evidence is consistent with phenomena described by Murphy et al. (1984). In addition, most of the forests (potential sources of fuel-wood) are located in the highly elevated mountainous regions. Casual observation of wood-fuel sales suggests supermarkets in the Lake Tahoe region report more fuel-wood sales than their San Francisco Bay Area counterparts. Lake Tahoe is located on the border between California and Nevada and its average elevation is 6229 feet above sea level. These data are consistent with the elevation impact results on wood burning. Without considering correlation effects, Eq. (4) below explains approximately 86% of the variation with the top seven variables selected from all candidate variables by using stepwise linear regression method:

$$\mathrm{AP} = 3069 + 2.342x_1 + 412.75x_2 + 102.96x_3 + 30x_4 - 45x_5 + 126.6x_6 - 23.5x_7, \qquad (4)$$

where χ_1 represents elevation; χ_2 is the locations of urban, or suburban, or rural; χ_3 is the ratio of retirement residents; χ_4 is the forest accessibility; χ_5 is the ratio of houses occupied by its owner; χ_6 is the ratio of households living on farming incomes; χ_7 is the percent of households in which the age of the head of the family is greater than 55. Location of urban, suburban and rural is a categorical variable that is mostly treated as a group of binary dummy items for analyzing the significance of location. However, our test shows that the mean numbers of wood-heating households is a linear function of location of urban, suburban and rural areas after representing them with ordinal numbers. The advantage of this transformation to ordinal numbers is being able to analyze the significance of location as a whole instead of as a group of categorical variables.

Forest accessibility is the second most important variable, by itself explaining approximately 56% of variation of RWB activity-potential. However, a high correlation between elevation and forest accessibility cause this variable to be ranked 4th in the stepwise analysis. The higher number of households using wood burning that relates to forest accessibility certainly also relates to elevation and urban/rural landuse types. Our linear regression analysis shows that elevation has more influences than forest accessibility. Both variables are good predictors of wood burning activity-potentials. Sexton et al. (1985) reported that the mean monthly temperature is important factor influencing wood burning activity of households. The high correlation among variables of elevation, HDD and forest accessibility renders HDD insignificant when elevation and forest accessibility variables are included. We also discovered that there is no advantage in dividing non-urban classified regions into suburban and rural.

3.2. Impacts of demographical characteristics

The analysis identifies several demographic characteristics that are directly related to wood burning practices: proportions of retired income χ_3, ratio of owner-occupied houses, ratio of households living on farm income χ_6, statistics on age groups of residents χ_7, and the ratio of owner-occupied properties χ_5. Although the variable on age of houses is related to RWB activities, as displayed in Fig. 2a, its impact is insignificant compared to other variables selected in our statistical analysis. Elderly people require more economic heat energy, while wood-fuel is an economic heating source (Fig. 2b). A higher percentage of farm households are primary wood burners than other types of households, because farm households generally have better accessibility to forest fuel-wood and backyard fire fuel-wood. Owner-occupied households show a higher occurrence of primary wood burning than non-owned residences (Fig. 2c). Family residents whose ages range between 35 and 54 are more likely to have small children and economic pressures, and are therefore more likely to use cost-effective fuels.

The stepwise linear regression method is a valuable first step in identifying independent variables that correlate with potential wood burning activity. These identified important variables were satisfactory to expert conceptual assessment. The dependent variable used in the establishment of this model was from US census 1990 data; therefore, collection of updated information was required in order to calibrate and validate the model.

Fig. 2. Model validations with demographic breakdown of % households using wood burning as primary heating sources: (a) burning activity by house age; and (b) burning activity by occupant age (using oldest household member's age); and (c) burning activity by ownership status (owner or non-owner).

4. Survey design and sampling strategy for validation

A survey was designed and given in person and over the telephone to households in the study area in order to collect updated information on the distribution and variation of RWB activity. It was implemented using a stratified random sampling protocol over the entire study region. The data from the survey were used to validate the statistical analysis results for predicting the activity-potential of RWB. The sampled information also includes ratio of wood stoves over fireplaces, and average annual wood consumption per household, as shown in Fig. 1.

4.1. Survey design

The initial survey extracted information on the potential for wood burning activity, which is the key for accurate emission estimation from residential fuel-wood combustion. Ancillary data collected were location, duration of average burning event for both weekdays and weekends, estimated number of annual burning events, and months that burning occurred. The location information in the survey was used to generate coordinates for each sampling point. The duration of the burning event was the average number of hours in each event. The estimated number of annual burning events was actually about the days of burning events. The months of burning occurred were detailed with information on which months when the wood burning was more likely used. A check box beside each month from January to December was designed for recording the multiple ticking.

Demographic information included type and age of dwelling, availability of wood burning fire appliances, tenure status, age of the oldest family member, and education level. The demographic characteristics from surveying households were designed to verify the linear model with the updated status of burning practices. The two items of demographic questionnaires, age of the oldest family member and tenure status of the house, were the variables in our linear regression Eq. (4). The survey was tested several times before the acceptance of its final version. The survey was formatted to ensure a high return rate through face-to-face or telephone interviews.

4.2. Stratified random sampling

Due to the large variation in household density over the study site, the survey was conducted with a stratified random sampling method to generate sample points at locations covering 28 counties. The stratification was based on areas classified as urban, suburban and rural to ensure an even distribution and a sufficient number of points for every unit area (Fig. 3a). Households close to the sampling points were visited or telephoned to until three successful samples were completed. Over 15,000 survey interviews, including phone calls and face-to-face visits, resulted in 731 successful acquired samples. The success rate from face-to-face visits was much higher than that from phone interviews. There are many phone numbers that are not valid any more, especially in suburb and rural area. The 15,000 survey interviews include all attempts, even phone numbers that do not exist any more. Three surveys at each sampling site were done to eliminate potential anomalies.

4.3. Validation

The 731 successfully completed samples were used for validating the linear model (Eq. (4)) of estimating activity-potential of RWB. The validation was first conducted for five spatial circumstances at study site: (1) urban and non-urban locations, (2) individual counties, (3) climatic zones, (4) terrain elevation classes, and (5) forest accessibility regions. Similarly, the model was also evaluated in various groups of demographic data, such as years of dwelling, age of the oldest family member, and occupant type (property owner or non-owner).

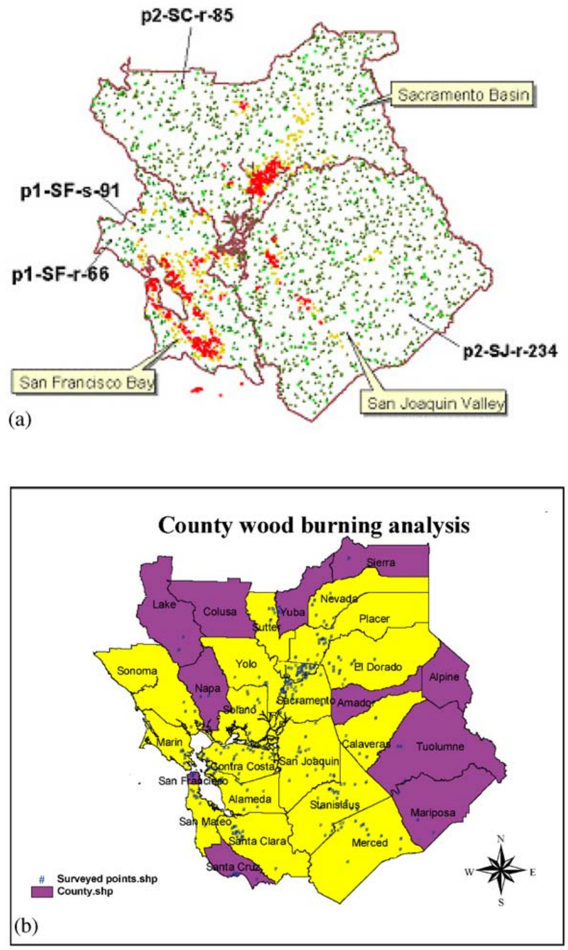

Fig. 3. Sampling points and their distribution in the study regions: (a) initial sampling points; and (b) successfully completed sample points.

Model performance in urban and non-urban classifications for three regions—Sacramento Valley, San Joaquin Valley and San Francisco Bay Area—is summarized in Table 1. According to the R^2-values, the model provided excellent estimates of surveyed percentages of households burning wood as a primary heating source in all three regions ($R^2 > 0.98$). However, the model overestimated for the non-urban areas about 2 times and underestimated the urban areas. Over-estimation of surveyed data for non-urban areas was due to insufficient samples over forested non-urban areas. Although stratified random sampling methods were applied to ensure the even distribution of the sampling points, survey response rate in forested non-urban area was very low due to the poor quality phone directory. These low-response forested areas usually have a high percentage of households burning wood as primary heating source. Therefore, the surveyed data under-represented the true conditions in non-urban locations.

For the county scenario, the model prediction and surveyed results were compared in 15 counties where we had sufficient survey points. The model prediction was plotted against data surveyed in each county (Fig. 4a). The model explained about 68% of the variations of the survey data. Model estimation matched the survey data very well in almost all counties. For example, in Nevada County, the high burning percentage in the survey matched model estimation. Nevada County is a heavily forested areas with high elevation. However, in Calaveras County, estimated values were much higher than those from the surveyed data. This unmatched situation occurred because the successfully completed samples were clustered in low elevation and non-forested areas. The surveyed result for this county was biased to low activity-potentials due to insufficient information for high elevation and forested areas (Fig. 3b).

There are six different climatic zones within the study area and the mean HDD among these climatic zones vary from 2643 to 5532. One of these zones is an unusual

Table 1
Percentages of households burning wood as heating source

	Non-urban		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%
R^2-values	0.9927		0.9959		0.981	

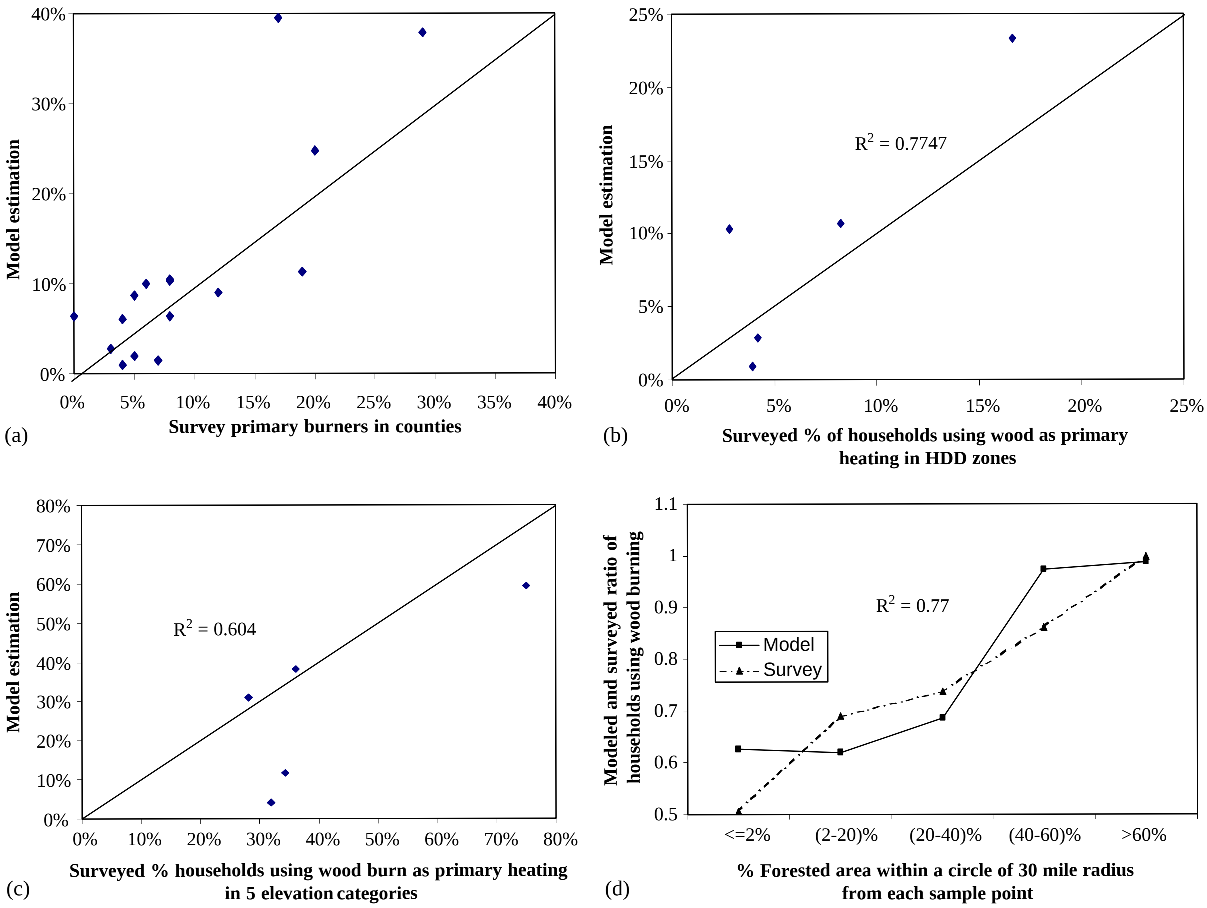

Fig. 4. Comparison of % surveyed households using wood burning as a primary heat source versus model estimation: (a) for county scenarios; (b) in five climatic zones; (c) in five elevation categories; and (d) in five forest accessibility groups.

region covered mainly by high elevation forest and has average HDD of 5532. Due to insufficient sample points in the high elevation region, validation in climatic conditions excluded this unusual zone. Model predication versus surveyed ratios of wood burning households for the remaining five climatic zones are plotted in Fig. 4b. The model is able to explain 77% of surveyed data. Two overestimations were in climatic zones in northern California and two underestimations were in coastal regions around central California.

The study region was naturally classified into five categories of DEM: (0, 77), (77, 244), (244, 488), (488, 798), and (789, 1694). With this division, the model explained about 60% of the surveyed ratios of wood burning households (Fig. 4c). Two underestimations in the low elevation range indicated that the model performed better in low elevation areas than in the high elevation regions. The model did not seem to perform better with DEM variation than in scenarios of climatic zones and counties. This phenomenon appears inconsistent with the regression result, which suggests that elevation was the most important factor in predicting potential wood burning activity. Actually, the two results described different things, because this analysis depended on the rules of classifying the DEM. This analysis was not intended to find the best classification rule. Instead, it was to use a classification case to examine the model performance against the survey result. This validation showed that the model performed satisfactorily with the variation of the DEM.

Finally, model performance was validated with five categories of forest accessibility characteristics. R^2-value for the comparison between model estimation and survey data was 0.77 (Fig. 4d). The model estimation and survey results were displayed against the five categories of forest accessibility. Two groups of data showed a good agreement in general trend in all cases. The trend indicated that the percent of households burning wood as a primary heating source increases with forest accessibility. Almost 100% of households were primary wood burners in areas where more than 60% forest surrounds their residences. However, the results showed a divergence at low forest accessibility areas. Optimizing the definition of wood burning as primary heating source might narrow the divergence.

5. Estimating $PM_{2.5}$ emission from wood stoves and fireplaces

$PM_{2.5}$ emission for a region was estimated as a function of fuel-wood consumption, the number of activity households, and combustion efficiency of the fire appliances. Of these three variables, the combustion efficiency (Cass and Fine, 2000) has been well studied and is available for various fire appliances and fuel-wood types (Radke et al., 2002). Recent advances in technology show promise in improving the assessment of the other two variables. Both fuel-wood consumption and the number of active fire appliances vary according to season and are spatially explicit. The proposed method of estimating activity-potential of RWC would improve the assessment of the number of active fire appliances by referring to spatial and demographic characteristics. Using different fire appliances and wood-fuel would result in vastly diverse $PM_{2.5}$ emissions. In this study, $PM_{2.5}$ emission was considered for two types of wood-fuel and two types of fire appliances. The two wood-fuel types were natural wood logs and manufactured wood. The two types of fire appliances were woodstoves and fireplaces. The woodstoves consisted of four subclasses: conventional uncertified, certified catalytic, uncertified catalytic, and fireplace with inserts.

Estimation of $PM_{2.5}$ emission has a general formula (Eq. (5)). Since the emission factors are different for woodstoves and fireplaces (Burnet et al., 1986), some variables in the equation must be replaced by the specific values for fireplaces or woodstoves.

$$\text{PM (tons)} = \alpha\beta E_r \times \text{NH} \times F, \tag{5}$$

where the α is the unit conversion factor set to 1/2000 for transferring from lbs to tons. β is the conversion factor for transferring from cord to tons, and a value of 1.16 is used in the case study (Houck and Tiegs, 1998). Two cords of wood-fuel are approximately one ton. The E_r (lbs/ton) is the emission factor for the combinations of fire appliances and wood-fuel types. The NH is the number of active households. The NH is designated NH_w for woodstoves and NH_f for fireplaces. F is the mean annual fuel consumption (tons of wood) per household. F is designated F_w for natural wood fuel and F_f for artificial (manufactured) wood fuel.

The values of NH_w and NH_f in this study were derived from RWC activity-potential discussed earlier. Calculation for the number of active woodstoves (NH_w) and number of active fireplaces (NH_f) was based on our survey results. The results showed that the ratio of active woodstoves over fireplaces is significant only between urban and non-urban classifications. The sampled ratios (2.17 for non-urban and 0.35 for urban) were used to separate the number of woodstoves and fireplaces from the activity-potential (total households using fire appliances).

Two methods were used to determine F_w and F_f. First, the annual mean wood-fuel consumption from individual woodstoves and fireplaces in urban and non-urban areas was collected from surveys in the study region. The average fuel consumption from woodstoves is 426 logs for non-urban and 437 for urban. For fireplaces, it is 376.8 for non-urban and 344.3 for urban. It is reported that, on average, 444 logs of natural wood is approximately one cord and one piece of artificial manufactured fuel log is about 4.95 lbs (Houck and Tiegs, 1998).

With reference to the above information from our survey, the annual mean wood fuel consumption from an individual woodstove, F_w, is estimated as 1.12 ton for non-urban and 1.15 ton for urban. The F_w is coordinated with the value of 1.23 cords (1.43 ton) consumed/unit/year calculated by Houck and Tiegs (1998) from eight household surveys in the State of Oregon. In a similar way, our surveyed F_f is 0.99 ton for non-urban areas and 0.9 ton for urban areas. The rate reported by Houck and Tiegs (1998) from the Oregon survey is 0.656 cords burned/unit/year (0.763 ton). Since the wood fuel consumption used in our study was based on survey from 731 households, our records are more robust. Unlike woodstoves, the survey results for fireplaces indicated that the ratio of aesthetic over primary wood heating households is 0.16 in non-urban areas and 0.21 in urban, meaning there would be one aesthetic for every 5 or 6 primary heating households. The average wood-fuel consumption from fireplaces is 1.28 cords (1.488 ton) for primary heating and is 0.3 cords (0.35 ton) for aesthetic heating.

With the parameter settings, NH and F described above, model estimated $PM_{2.5}$ emissions for each county in the study region are displayed in Fig. 5a. Figs. 5b, c and d represent the ratio of primary wood burning over total households, number of households with primary wood burning activity, and total households in general. The ratio is much higher in rural counties closer to forested and elevated areas (Fig. 5b). The ratio decreases when it is close to dense household counties, as shown in Fig. 5d. The spatial pattern of estimated emission is very similar to that of the number of households with primary burning activity. The similarity of these two patterns confirmed that the activity-potential is an important factor. The counties with the densest households are not necessarily the highest $PM_{2.5}$ emitters. For example, the total annual emissions from Alameda, Santa Clara, San Francisco, Sacramento and Contra Costa, were not the highest. Contrarily, the emission

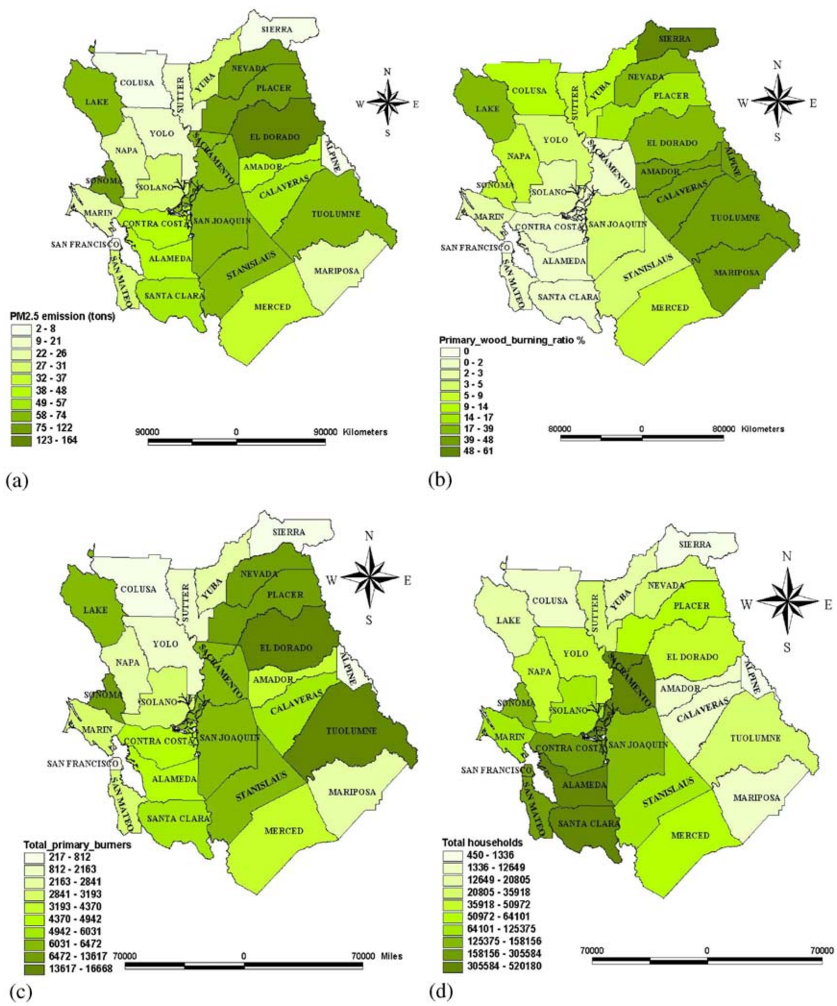

Fig. 5. $PM_{2.5}$ emission estimation for the State of California: (a) annual $PM_{2.5}$ emission estimated for each county; (b) the ratio of wood burning as primary heat source over total households; (c) the number of households burning wood as a primary heat source; and (d) total number of households.

from San Francisco County was almost the lowest among the 28 counties.

6. Discussion and conclusion

The modeling results verified that, in the number of households using either woodstoves or fireplaces, NH, is more sensitive than F in Eq. (5) for estimating $PM_{2.5}$ emission, since NH varied in wider range (50–11,000 households at the county level) than the mean annual wood fuel consumption, F (0.2–1.5 ton at an individual household). Therefore, an appropriate method to estimate NH would be essential to ensure a reliable estimation of $PM_{2.5}$ emission. The NH was proportional to the RWC activity-potential so that the resulted $PM_{2.5}$ was spatially dissolved at desired scales.

This study discovered that activity-potential of residential wood burning (RWC) is a function of spatial and demographic characteristics. The most important spatial characteristics are elevation, accessibility to forest areas, urban/non-urban classification, and climate conditions. The differences of activity-potential are significant in urban and rural areas. Elevation is the best predictor, with forest accessibility as a strong second place predictor. Variation of elevation implies change of local climate that increases or decreases demand for heat in a household. The forest accessibility affects wood burning activity because firewood is a cheap heating resource and convenient access to the resources could change heating habits. The analysis results also indicate that demographic characteristics were complementary to spatial characteristics in predicting RWC activity-potential. Employing these spatial and demographic data, the model is able to explain 86% of the variations in households using fire appliances for primary heating.

The modeling results demonstrated that the attributes on primary wood burning households in US Census 1990s data contains valuable information for predicting RWB activity. Although the data are dated (1990), the model established can be applied to an analysis of updated information. When the updated demographic data become available, the model performance could have two consequences: (1) it could be applied to the updated information without major modification; (2) coefficients of the model may be re-calibrated with updated activity-potential and demographic features without re-selecting variables.

The methods for extracting spatial and demographic variables are critical for allocating $PM_{2.5}$ emission from RWB. In particular, the simple methods for extracting urban/non-urban locations and forest accessibility could be useful in other research projects. With the combination of these demographic and spatial variables, the proposed model improved the spatial allocation of activity-potential RWB activity. Although information on primary wood burning households has been available since 1990, this study was the first effort to analyze spatial variation and demographic effects on RWB.

Because of the complexity of the application, a multivariate linear regression model is unlikely to be the optimum method to model activity-potential of primary wood burning. Using linear statistical analysis is an important step in identifying significant factors affecting human use of wood as a heat source. Moreover, this linear model sufficiently estimates activity-potential of RWB and facilitates improved estimation of $PM_{2.5}$ emission. The linear analysis convinced us that a further study using a non-linear modeling approach might be appropriate for describing the mechanics of the causal relationship in this human social ecological system.

Although RWC activity-potential in a location would change dynamically with population movement and socio-economic and government policies, the change is relatively insignificant within the period of a year. The activity-potential represents the number of households using wood burning as a primary heat source and likely increases when the temperature decreases. Further, variation in percentage of activity-potential with seasons would be different due to shorter days in early spring and late autumn, and longer days in the middle of winter. A research program from Wentz et al. (2002) demonstrated that concentrations of atmospheric carbon dioxide in winter are much higher in an urban environment.

The distribution of the percentage of activity-potential and the daily burning duration across the seasons are being considered in an on-going research. An accurate estimation of activity-potential is essential for modeling $PM_{2.5}$ emission on a seasonal and daily basis. Predicting $PM_{2.5}$ at smaller time scale requires incorporating a way of assessing wood fuel consumption. At present, the survey is designed for collecting information on mean annual wood fuel consumption per household; therefore, the predicted $PM_{2.5}$ is about the annual average. The prediction at an annual scale might be inappropriate for many applications.

Radke et al. (2002) discussed a method of modifying the model for emission allocation at smaller time scales, such as monthly and daily. In the modification, the mean annual wood fuel consumption, F, is calculated by integrating daily and then monthly consumptions. The daily wood fuel consumption is allocated by referencing the energy demands of individual households corresponding to HDDs (daily climate condition). According to the survey, mean daily burning hours are 5.5 for primary fireplace burners and 2.1 h for aesthetic fireplace burners. For woodstoves, the average burning hours per day is 11.9 for primary burners and 4.2 h for aesthetic burners. Average burning wood fuel days are 53 for fireplaces and 59 for woodstoves.

This study focuses on the activity-potential of primary wood burning sources rather than that of aesthetic heating. It has been recognized that there is a requirement for a consistent definition of households burning wood as primary heating source. By analyzing the surveyed data, we indicated that using 90 burning events as the threshold to distinguish between primary and aesthetic heating is appropriate. The statistics on primary wood burning in the US Census 1990 databases are also from surveys. Opinion of interviewees on if they were primary or aesthetic wood burners could be influenced by their location and personal characteristics, including education. As a consequence, the surveyed results on this question are fuzzy in nature. The classification between primary and aesthetic heating in this study was based on the average number of hours of using fire appliances each year. We defined a household as a primary wood burner if they amassed more than 90 h of fire appliance use within a year. Although this definition was well correlated with the results in the 1990 US Census databases, these definitions are empirically based and insufficient for use as a general rule for different locations and communities. A dedicated study is required to define the primary and aesthetic RWB consistently and accurately.

Information for model creation and validation is surveyed at the study region, limiting our model to local climate variation. The model might overestimate for southern California and underestimate for northern California. Radke et al. (2002) suggested a modification for the model for a large-scale area by considering latitude as an additional variable.

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