Effectiveness of Residential Wood-Burning Regulation on Decreasing Particulate Matter Levels and Hospitalizations in the San Joaquin Valley Air Basin

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Objectives. We examined the impact of Rule 4901, aimed at reducing residential wood burning, on particulate matter levels and hospitalizations in the San Joaquin Valley Air Basin (SJVAB).

Methods. Using general linear mixed models and generalized estimating equation models, we compared levels of particulate matter and of hospital admissions (age groups = 45–64 and ≥ 65 years) in the SJVAB for cardiovascular disease (CVD), ischemic heart disease (IHD), and chronic obstructive pulmonary disease during the burn seasons before (2000–2003) and after (2003–2006) implementation.

Results. After implementation, we observed reductions of 12%, 11%, and 15% in particulate matter 2.5 micrometers in diameter or smaller (PM2.5), and 8%, 7%, and 11% in coarse particles, in the entire SJVAB and in rural and urban regions of the air basin, respectively. Among those aged 65 years and older, Rule 4901 was estimated to prevent 7%, 8%, and 5% of CVD cases, and 16%, 17%, and 13% of IHD cases, in the entire SJVAB and in rural and urban regions, respectively.

Conclusions. The study suggests that Rule 4901 is effective at reducing wintertime ambient PM2.5 levels and decreasing hospital admissions for heart disease among people aged 65 years and older. (*Am J Public Health.* 2015;105: 772–778. doi:10.2105/AJPH.2014.302360)

The San Joaquin Valley Air Basin (SJVAB) extends from the Sacramento–San Joaquin Delta in the north to the Tehachapi Mountains in the south and from coastal mountain ranges in the west to the Sierra Nevada in the east. The SJVAB is an agricultural valley and includes the counties of Fresno, Kern, Kings, Madera, Merced, San Joaquin, Stanislaus, and Tulare. The San Joaquin Valley has hot dry summers and cold rainy winters characterized by dense low fog. Surrounded by mountains and lacking prevailing winds to disperse pollutants, the valley has historically had some of the worst air quality in California.[1,2] From 2001 to 2003, the ambient levels of PM2.5 (particulate matter ≤ 2.5 μm in diameter) in the SJVAB reached concentrations that were substantially greater than the 24-hour national standard at that time (65 $\mu g/m^3$).[3] Combustion of solid fuels, such as wood, has been identified as the largest individual source of particulate matter during winter months, and has been estimated to generate as much as 23 tons per day of particles from smoke, soot, and ash.[4]

The most severe particulate air pollution episodes in the SJVAB historically have occurred during winter months (November–February), during which residential fuel combustion has been estimated to contribute more than 20 metric tons per day of PM2.5 pollution to the SJVAB.[5] Because of this poor air quality, and to help attain the National Ambient Air Quality Standards and improve health, the San Joaquin Valley Unified Air Pollution Control District in 1992 adopted Rule 4901, which aimed at reducing emissions of carbon monoxide and particulates from residential wood-burning fireplaces and heaters[6] during the burn season (November–February) and establishing a public health education program to reduce wood-burning emissions. The rule was amended in 2003 to require mandatory curtailment of residential wood burning when air quality was forecast to be poor—that is, an air quality index of at least 150 (approximately 65 $\mu g/m^3$ of PM2.5)—and other measures were taken to reduce the impact of residential burning.[7] Using the US Environmental Protection Agency's software program BenMAP, Lighthall et al. estimated that the potential health benefits of the rule would be substantial, including reductions in several morbidity endpoints.[8]

Epidemiological studies have found that exposure to the constituents of residential wood smoke is associated with reduced lung function, increased respiratory symptoms, and exacerbation of respiratory diseases, including chronic obstructive pulmonary disease (COPD) and asthma as well as respiratory-related emergency department and hospital visits.[9–23] Some studies have also shown that wood smoke is associated with adverse cardiovascular health effects.[13,14,24–27] In addition, controlled studies of wood smoke exposure found increases in markers of inflammation and coagulation, irritated mucosa, and increases in central arterial stiffness as well as a reduction in heart rate variability.[26,28–30]

Concern over air quality has prompted several communities in the SJVAB to work with the district to regulate and ban residential burning when air quality forecasts are poor. These regulations have been coupled with public education, and there are indications that some of these campaigns have been successful in improving air quality.[4] The 2012 PM2.5 plan for the San Joaquin Valley includes a descriptive analysis of Rule 4901's effectiveness in reducing PM2.5 concentrations in the Fresno area.[31] Since the regulation was fully implemented in 2003, however, no multivariate analysis has been performed to evaluate the changes in PM2.5 levels and health in response to district actions to regulate residential wood burning.

We therefore evaluated the effectiveness of Rule 4901 in decreasing wintertime particulate matter such as PM2.5 and coarse particles in the SJVAB and in reducing the burden of wintertime hospital admission rates for cardiovascular disease (CVD), ischemic heart disease (IHD), and COPD in adults aged 45 to 64 years and in the elderly (≥ 65 years) residing in the SJVAB. Because the prevalence of wood burning as a heating fuel may vary by region, we also performed stratified analyses on the rural and urban regions of the SJVAB to address the nonuniformity of wood burning as a heating fuel among different regions of the valley. Although the rule was adopted in 1992, enforcement of the rule did not begin until the 2003 amendment. Therefore, for this study, we evaluated the impact of the rule on health and exposure during the burn season (November–February) for the 3 years before and after the 2003 amendment.

METHODS

We extracted data for ambient PM2.5 and coarse particle concentrations (derived by subtracting PM2.5 data from PM10 data) for the SJVAB from the California-based National Air Monitoring Stations/State and Local Air Monitoring Stations (NAMS/SLAMS) for the burn seasons (November–February) of 2000 through 2006.[32] Particulate matter measurements were taken by NAMS/SLAMS every 1, 3, or 6 days depending on the monitoring station. To account for the missing daily particulate matter data among monitoring sites, we performed regressions to search for the best available predictive relationship between each site and all other sites within the closest distances. Using geographic information system (GIS) software (ArcMap 10.0; Esri, Redlands, CA), we then estimated a statewide daily concentration surface of PM2.5 and coarse particles at ground level by modeling a pollutant surface using the Inverse Distance Weighting method[33–35] and assigning the results from this interpolation to the centroid of each zip code in the SJVAB. We assigned rural and urban regions the Inverse Distance Weighting interpolated concentration that produced the least amount of error on the basis of the available monitoring data restricted to a 50-kilometer radius. However, when no monitor was located within the 50-kilometer radius, the model would assign the closest monitor value outside that radius. We obtained daily meteorological data from the California Irrigation Management Information System.[36]

Hospital Admission Data

We obtained data on daily hospital admissions for cardiovascular- and respiratory-related causes from the California Office of Statewide Health Planning and Development for the winter periods from 2000 to 2006. The hospital admission records include the date of admission, place of residence (zip code), age of the patients, and primary diagnoses. Our analysis focused on hospital admissions for CVD (*International Classification of Diseases, Ninth Revision*[37] [*ICD-9*] codes 390–429), IHD (*ICD-9* codes 410–414), and COPD (*ICD-9* codes 490–496) among adults and the elderly. We obtained the daily morbidity counts by zip code for each category of hospital admissions by summing the number of hospital admissions.

Statistical Analysis

We used a 2-tailed *t* test to determine whether the following factors showed significant differences (defined as $P \le .05$) between the pre– and post–Rule 4901 periods: PM2.5 and coarse particle daily averages, no-burn days, high PM2.5 days, and meteorological factors (minimum daily average temperature, maximum daily average temperature, minimum daily average dew point, maximum daily average dew point, and wind speed).

For the multivariate analyses, we constructed a dummy variable (0 for before November 2003, 1 for after November 2003) to model pre– and post–Rule 4901 periods, respectively. We dichotomized the no-burn-day variable, with a no-burn day (scored 1) defined as a day when air quality was forecast to reach an air quality index of at least 150 (approximately 65 $\mu g/m^3$ of PM2.5) and wood burning was therefore banned. We also created a binary variable for day of the week (1 for weekend, 0 for weekday). We derived socioeconomic variables such as percentages of poverty, unemployment, and low education at the zip code level from US Census 2000 data.

We performed general linear mixed models to evaluate the effect of Rule 4901 on the daily mean PM2.5 and coarse particle levels before and after the regulation. The models accounted for the fact that there were repeated measurements within the same zip code. The study period covered only the wintertime (November–February), so we did not include seasonality in the models. We examined the effect of potential confounding factors such as temperature, relative humidity, average wind speed, calendar years, day of the week, and no-burn days for the linear mixed models. Only calendar years and no-burn days showed an increase in the change in estimate of the intervention by more than 10%; therefore, we adjusted the final linear mixed models for these 2 items.

We analyzed the daily CVD, IHD, and COPD hospital admissions using generalized estimating equations (GEE). We fitted the multivariate analysis using GEE with Poisson distribution and implemented it using the GENMOD procedure in SAS version 9.1.3 (SAS Institute, Cary, NC), correcting to account for correlation within the same zip code. We used the change in estimate as the criterion to select confounders for this study. On the basis of the 10% change in estimate of the intervention variable, we adjusted day of the week, no-burn days, and percentage of poverty into the final GEE models to control for confounder effects.

For both linear mixed models and GEE models, we also performed stratified models on rural regions (defined as zip codes with an overall population of fewer than 500 people per square mile) and urban regions.[38]

Hospital Cases Prevented by Rule 4901

We applied the following formula to calculate the preventable fraction (PF) of hospital cases for CVD, IHD, and COPD[39,40]:

$$(1)\quad PF = (1 - RR)^{*}100,$$

where RR is the rate ratio comparing the periods before and after Rule 4901.

When we calculated the PF, hospital cases in the study population prevented by Rule 4901 could be estimated as follows:

$$(2)\quad \text{Prevented cases} = PF^{*}\text{expected cases},$$

where “expected cases” is defined as the expected number of cases among the

TABLE 1—Wintertime Averages for PM2.5 and Coarse Particles Before and After Implementation of Rule 4901: San Joaquin Valley (California) Air Basin, 2000–2006

	SJVAB		Rural Regions		Urban Regions	
	Before Rule 4901, Mean ±SD	After Rule 4901, Mean ±SD	Before Rule 4901, Mean ±SD	After Rule 4901, Mean ±SD	Before Rule 4901, Mean ±SD	After Rule 4901, Mean ±SD
No-burn days	15 ±3	100 ±45*	15 ±3	99 ±44*	15 ±3	100 ±47*
Days with AQI ≥ 150	35 ±21	12 ±7*	32 ±20	12 ±7*	42 ±23	14 ±8*
PM2.5 particles, μg/m^3	30.76 ±22.88	26.10 ±16.56*	29.18 ±22.42	25.17 ±16.47*	35.62 ±23.59	28.97 ±16.50*
Coarse particles, μg/m^3	19.02 ±16.91	14.63 ±12.09*	19.03 ±16.99	14.72 ±12.14*	18.99 ±16.71	14.41 ±11.97*
Temperature, °F	61.15 ±13.70	65.70 ±10.66	59.70 ±13.76	65.80 ±10.02	64.02 ±13.10	65.56 ±11.46
Dew point, °F	46.04 ±7.40	47.81 ±6.34	45.77 ±8.10	48.22 ±7.26	46.57 ±5.74	47.26 ±4.81
Wind speed, mph	3.63 ±1.46	3.75 ±1.65	3.81 ±1.58	4.07 ±1.85	3.27 ±1.08	3.31 ±1.19

Note. AQI = air quality index; PM2.5 = particulate matter ≤ 2.5 μm in diameter; SJVAB = San Joaquin Valley Air Basin. On no-burn days, air quality is forecast to reach an AQI equal to or greater than 150 (approximately 65 μg/m^3 of PM2.5) and wood burning is banned. Rural regions were defined as zip codes with an overall population of fewer than 500 people per square mile.
*P < .05 (comparing post-Rule 4901 with pre-Rule 4901).

population if Rule 4901 was not enforced in the SJVAB.

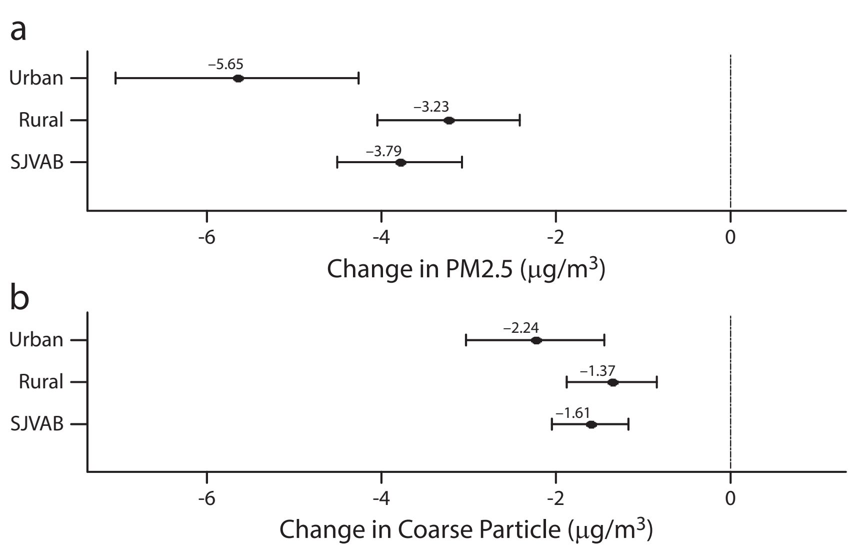
RESULTS

After the amendment of Rule 4901 in 2003, on average, the total number of days in the SJVAB during which the air quality index was greater than or equal to 150 was reduced from 35 (before Rule 4901) to 12 (after Rule 4901; Table 1). From November 2000 to February 2006, the total number of wintertime days during which residential wood burning was banned increased from 15 to 100 days. Also, as illustrated in Table 1, the daily mean concentrations of PM2.5 and coarse particles in the entire SJVAB, in rural regions, and in urban regions showed statistically significant reductions after Rule 4901. The daily average temperature, dew point, and wind speed showed no statistically significant differences.

After controlling for calendar year and no-burn days, we observed statistically significant reductions in PM2.5 and coarse particles from the pre– to the post–Rule 4901 period (Figure 1). PM2.5 levels were reduced by 3.79 μg/m^3, 3.23 μg/m^3, and 5.65 μg/m^3 and coarse particle levels were reduced by 1.61 μg/m^3, 1.37 μg/m^3, and 2.24 μg/m^3 in the SJVAB as a whole, in rural regions, and in urban regions, respectively.

We calculated hospital admission rates for CVD, IHD, and COPD for 2 age groups—adults (45–64 years) and the elderly (≥ 65 years; Table 2). From the pre– to post–Rule 4901 period, the hospital admission rates per 1000 for adults decreased from 41.0 to 39.9 for CVD, from 23.0 to 21.5 for IHD, and from 7.2 to 6.5 for COPD. Among the elderly, the admission rates per 1000 decreased from 152.2 to 81.1 for CVD, from 60.7 to 31.6 for IHD, and from 23.7 to 13.7 for COPD—reductions approximately 3 times greater than those for adults aged 45 to 64. Interestingly, the rates of CVD, IHD, and COPD were always more than 1.5 times higher in the rural regions than in the urban regions.

Among adults, the adjusted rate ratios for CVD, IHD, and COPD were not statistically significantly reduced by Rule 4901 in the



Note. PM2.5 = particulate matter ≤ 2.5 μm in diameter. The results, which compare the pre- and post-Rule 4901 periods (for November through February), are from a combination of data from all 8 counties in the San Joaquin Valley Air Basin (SJVAB). Rural areas were defined as zip codes with an overall population of fewer than 500 people per square mile. The models were adjusted for year and no-burn days.

FIGURE 1—After implementation of Rule 4901, reduction of (a) wintertime PM2.5 and (b) wintertime coarse particles: San Joaquin Valley (California) Air Basin, 2000–2006.

TABLE 2—Wintertime Annual Hospital Admission Rates per 1000 Population Over the 3-Year Periods Before and After Implementation of Rule 4901: San Joaquin Valley (California) Air Basin, 2000–2006

	SJVAB		Rural Regions		Urban Regions	
	Before Rule 4901, Mean	After Rule 4901, Mean	Before Rule 4901, Mean	After Rule 4901, Mean	Before Rule 4901, Mean	After Rule 4901, Mean
Aged 45–64 y						
Cardiovascular disease	41.0	39.9	52.2	49.9	26.5	26.9
Ischemic heart disease	23.0	21.5	29.3	27.3	14.7	14.0
Chronic obstructive pulmonary disease	7.2	6.5	8.8	7.9	5.0	4.6
Aged ≥ 65 y						
Cardiovascular disease	152.2	81.1	181.4	100.0	99.7	58.8
Ischemic heart disease	60.7	31.6	77.5	39.4	41.0	22.6
Chronic obstructive pulmonary disease	23.7	13.7	30.2	16.5	16.1	10.3

Note. SJVAB = San Joaquin Valley Air Basin. Results are from a combination of data from all 8 counties in the SJVAB. Rural regions were defined as zip codes with an overall population of fewer than 500 people per square mile.

SJVAB as a whole or in rural or urban regions (Table 3). Among the elderly, however, the adjusted rate ratios for CVD were reduced by 7%, 8%, and 5%, and those for IHD by 16%, 17%, and 13%, in the SJVAB, rural regions, and urban regions, respectively. The magnitude of the association between Rule 4901 and the health outcomes was stronger in the rural than in the urban regions, although a similar pattern was seen for both regions. Although we observed reductions in rates of hospital admissions for COPD, the adjusted rate ratios were not statistically significant.

Calculations based on formula 2 (see "Methods" section) suggest that Rule 4901 prevented 7% (n = 311) and 16% (n = 111) of the hospital admissions for CVD and IHD, respectively, in the elderly group. We also estimated reductions of 283 CVD cases (PF = 8%) and 101 IHD cases (PF = 17%) for rural regions, and reductions of 48 CVD cases (PF = 5%) and 20 IHD cases (PF = 13%) for urban regions.

DISCUSSION

Our results provide evidence for the contribution of Rule 4901 in reducing wintertime PM2.5 and coarse particle levels in the SJVAB. The findings of this study show that, on average, the rule was associated with a reduction in the level of ambient PM2.5 of 12% in the SJVAB as a whole, and that it also led to statistically significant reductions in wintertime PM2.5 levels in both rural and urban regions of the SJVAB. We also observed a similar pattern of reduction for coarse particles. The reduction in PM2.5 seen in our study following Rule 4901 is in line with the results of 2 studies conducted in Fresno during the 1995–1996[41] and 2003–2004[42] winters. The earlier study showed that wood smoke contributed about 42% of the ambient PM2.5 mass in the wintertime and suggested that the source of PM2.5 was likely residential wood burning.[41] The second study indicated that, on average, wood smoke accounted for about 18% of PM2.5 mass in Fresno. Although these studies were conducted independently, the results provide indirect evidence for a reduction of wintertime PM2.5 mass in Fresno between those 2 time periods.

We observed a decreased risk of hospitalization for CVD and IHD among the elderly, in the SJVAB as a whole and in both rural and urban regions, after the amendment of Rule 4901. In addition, although the impact of Rule 4901 on CVD and IHD was not statistically significant for the younger group, our PF calculation suggests that between 2003 and 2006, 39 CVD cases (PF = 3%) and 58 IHD cases (PF = 8%) were prevented in the 45–64 year age group by implementation of Rule 4901. Our results also show a decreased risk of hospitalization for COPD in the SJVAB as a whole and in rural and urban regions, but the associations were not statistically significant. It is possible that these findings lacked statistical significance because the number of cases of COPD was too small to allow detection of the effects of Rule 4901.

Using data from the 2000 and the 2010 census (not shown), we compared percentages of households burning wood as a heating fuel, as this could have influenced the air quality results. We found no change between 2000 and 2010, therefore concluding that the reduction in particulate matter levels was likely related to Rule 4901. The census data showed that 8%, 10%, and 1% of the households in the SJVAB, rural regions, and urban regions, respectively, used wood as their heating fuel. The rural region, with the highest percentage of residential wood burning, also had substantial reductions in the burden of CVD and IHD among the elderly.

The heterogeneity of the association between Rule 4901 and CVD, IHD, and COPD in the rural and urban regions could reflect differences in the characteristics of households, such as the type and usage of household heating sources or cooking frequency. In addition, the emissions from residential wood burning contain a complex mixture of pollutant components, and the effects of exposure to this diverse mixture could also vary in different

TABLE 3—Adjusted Rate Ratios (RRs) Comparing Wintertime Hospitalizations Before and After Implementation of Rule 4901: San Joaquin Valley (California) Air Basin, 2000–2006

	Aged 45–64 Years, RR (95% CI)	Aged ≥ 65 Years, RR (95% CI)
Cardiovascular disease		
SJVAB	0.97 (0.90, 1.05)	0.93 (0.89, 0.97)
Rural	0.95 (0.85, 1.06)	0.92 (0.87, 0.98)
Urban	1.01 (0.95, 1.07)	0.95 (0.92, 0.99)
Ischemic heart disease		
SJVAB	0.94 (0.84, 1.05)	0.84 (0.78, 0.90)
Rural	0.94 (0.81, 1.08)	0.83 (0.75, 0.91)
Urban	0.95 (0.87, 1.03)	0.87 (0.82, 0.93)
Chronic obstructive pulmonary disease		
SJVAB	0.90 (0.78, 1.05)	0.93 (0.83, 1.04)
Rural	0.90 (0.74, 1.10)	0.91 (0.78, 1.07)
Urban	0.91 (0.78, 1.06)	0.95 (0.86, 1.06)

Note. CI = confidence interval; SJVAB = San Joaquin Valley Air Basin. Results are from a combination of data from all 8 counties in the SJVAB. Rural areas were defined as zip codes with an overall population of fewer than 500 people per square mile. The models were adjusted for calendar year, no-burn days, weekend, and poverty. *International Classification of Diseases, Ninth Revision,* codes were as follows: for cardiovascular disease, codes 390–429; for ischemic heart disease, codes 410–414; for chronic obstructive pulmonary disease, codes 490–496.[37]

environments. For example, the amount of wood-smoke particles in an area is highly dependent on the relative number of wood-fueled residential combustion appliances, the frequency of use, and the burn rate, as well as wood species, wood quality,[43–45] and wood stove operation.[46,47] The lack of data on factors related to the combustion type, activity, and conditions, and our inability to adjust for these household-level potential confounders in our analyses, may at least partially explain results that were not statistically significant. However, these issues could not be explored further because of the ecological design of this study. In addition, we were unable to assess the contribution of and variability in indoor exposures related to different household characteristics. Other factors that could influence the results include demographic trends that are unrelated to air quality, such as access to health care. In addition, Wallace[48] reported that in the Environmental Protection Agency's PTEAM study there was a substantial number of unknown indoor sources that contributed up to 25% of indoor PM2.5. Therefore, a contribution of indoor PM2.5 from other unidentified sources cannot be discounted.

Our study methods and findings had several limitations. As in most air pollution epidemiological studies, we used the available ambient PM2.5 monitoring data from central outdoor monitoring stations and assumed that an average of the ambient PM2.5 measurements was representative of the complex spatial and temporal pattern of exposures over a large area.[49,50] Smith et al.[51] have shown that in communities where most households use fireplaces, the intake fraction (fraction of material released into the environment that is actually inhaled) can be substantially higher than that for typical local outdoor sources, since the smoke may sit in the area among the houses in what is called "neighborhood pollution." Such pollution may not be reflected by ambient monitoring data, but nevertheless it could substantially influence localized exposures.[51] Furthermore, because of the ecological nature of the CVD, IHD, and COPD data for hospitalizations, we could not isolate the clinical implications of each of those diseases. The overlapping and interrelated nature of those diseases was unrelated to the status of disease and exposure assignment in our study. In general, this type of bias does not influence the association between effectiveness of the rule and hospitalization rate, although in some circumstances it might bias the association away from the null.[52]

A recent study showed that concentrations of black carbon, which served as a wood-smoke indicator in the study, were higher in residential areas than at central monitors.[53] Other studies conducted in the United States[41,42,54–56] have suggested that residential wood burning is a significant source of wintertime ambient PM2.5, and that localized PM2.5 levels due to residential wood burning can be up to 25% higher than levels recorded at central monitors. Our use of central-site monitoring data may therefore have led to an underestimation of the effectiveness of Rule 4901 on PM2.5 reductions, especially in areas with a high prevalence of wood-heating sources during the winter.

A recent study has reported that in households that burned wood for heating, personal exposures were highly correlated to indoor levels but less so to outdoor levels.[57] However, the current study found an impact on health from outdoor PM2.5, including from wood smoke. Therefore, when examining the impacts of residential wood-smoke exposures on health, it is important to consider the fact that such exposures can occur both from ambient outdoor air entering the home and from indoor air as a result of direct release from heating devices. An important area for future study is determination of the relative contributions of indoor versus outdoor wood-smoke exposures to overall health impacts.

No previous published studies examined the effect of residential wood-burning rules on either outdoor air quality or health. Ours is the first study to investigate the impacts of residential wood-burning regulations on both the reduction of ambient air pollution and improvements in health in adults and the elderly.

Our results provide evidence linking the effectiveness of Rule 4901 residential wood-burning regulations to decreases in the burden of hospital admissions for CVD and IHD, particularly among the elderly, as well as reductions in wintertime ambient PM2.5 levels. However, because total exposure is a result of both indoor and outdoor exposure, a careful evaluation of indoor wood-smoke exposures is needed to better assess the efficacy of residential wood-burning regulations. ■

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Contributors

P.-S. Yap, the study principal investigator, led the development of the study design, conducted the statistical analysis, interpreted and summarized the findings, and drafted the article. C. Garcia, the study co-investigator, developed the exposure study design and geographic exposure assessment models and assisted with the overall design and interpretations of the findings.

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Human Participant Protection

This study was approved by the Committee for the Protection of Human Subjects of the California Health and Human Services Agency.

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