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The contributions of emissions and spatial microenvironments to exposure to indoor air pollution from biomass combustion in Kenya.

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Acute and chronic respiratory diseases, which are causally linked to exposure to indoor air pollution in developing countries, are the leading cause of global burden of disease. Efforts to develop effective intervention strategies and detailed quantification of the exposure–response relationship for indoor particulate matter require accurate estimates of exposure. We used continuous monitoring of indoor air pollution and individual time-activity budget data to construct detailed profiles of exposure for 345 individuals in 55 households in rural Kenya. Data for analysis were from two hundred ten 14-hour days of continuous real-time monitoring of concentrations of particulate matter ≤ 10 µm in aerodynamic diameter and the location and activities of household members. These data were supplemented by data on the spatial dispersion of pollution and from interviews. Young and adult women had not only the highest absolute exposure to particulate matter (2,795 and 4,898 µg/m³ average daily exposure concentrations, respectively) but also the largest exposure relative to that of males in the same age group (2.5 and 4.8 times, respectively). Exposure during brief high-intensity emission episodes accounts for 31–61% of the total exposure of household members who take part in cooking and 0–11% for those who do not. Simple models that neglect the spatial distribution of pollution within the home, intense emission episodes, and activity patterns underestimate exposure by 3–71% for different demographic subgroups, resulting in inaccurate and biased estimations. Health and intervention impact studies should therefore consider in detail the critical role of exposure patterns, including the short periods of intense emission, to avoid spurious assessments of risks and benefits. Key words: Africa, biomass combustion, exposure assessment, field study, household energy, indoor air pollution, particulate matter, public health.

Acute respiratory infections and chronic respiratory diseases (obstructive pulmonary disease in particular) together account for > 10% of the global burden of disease (1-3). In 1997 and 1998, acute lower respiratory infections were the leading causes of death from infectious diseases, with an estimated 3.7 and 3.5 million deaths worldwide for the 2 years, respectively (3.4). Exposure to indoor air pollution, especially to particulates, resulting from the combustion of biomass (wood, crop residues, dung, and charcoal) has been implicated as a causal agent of respiratory and eye diseases (including cataracts, blindness, and possibly conjunctivitis) (5–12). This association, coupled with the fact that globally more than two billion people rely on biomass as their primary source of domestic energy, has put preventive measures to reduce exposure to indoor air pollution high on the agenda of international development and public health organizations (1,13–15).

For efficient and successful design of measures to reduce exposure to indoor air pollution, it is necessary to determine the factors that influence the level of exposure and the relative contributions of each. These factors include household energy technology (the fuel–stove combination), housing characteristics, and behavioral determinants of exposure such as the amount of time spent inside the house or near the cooking area. Accurate measurement or estimation of exposure is also essential for quantifying the exposure–response relationship for indoor particulate matter. Numerous epidemiologic studies on the health impacts of indoor air pollution have used indirect measures, such as fuel or housing type, as proxies for personal exposure (16). Given the nearly universal use of biomass fuels in rural areas, this indirect approach to exposure estimation artificially clusters numerous people into a single exposure category. However, recent findings on large variations in emissions of individual stove types (15,17) or in exposure within individual households (18,19) illustrate that aggregate analysis and grouping of individuals artificially reduces the variability of the explanatory variable in the exposure–response relationship and therefore decreases the reliability of the estimation of its parameters. From a public health policy perspective, ignoring the variability of individual technologies and intrahousehold variation in exposure may dramatically change the relative importance of various strategies for reducing exposure to indoor air pollution.

The use of personal monitors has been an alternative to the indirect exposure measures (7,20). Although personal monitors resolve the issue of exposure estimation, with most personal monitors exposure is aggregated over time and space. This limits predictive assessment of various intervention strategies and prevents incorporation of the high-intensity emission episodes that commonly occur during the combustion of biomass fuels.

In this paper, we integrate extensive quantitative and qualitative data on individual time-activity budgets, household demographic characteristics, and continuous real-time monitoring of indoor air pollution to construct personal profiles of exposure to particulate matter resulting from biofuel combustion. Data used in this paper were collected between 1996 and 1999 as part of an ongoing study of the relationship among energy technology, indoor air pollution, and public health. We conducted continuous real-time monitoring of indoor air pollution (particulate matter and carbon monoxide) in 55 houses for 14–15 hr/day for > 200 days. During this time we also recorded the location and activities of household members, with emphasis on energy and exposure-related variables. We complemented these data with extensive interviews with household members and local extension workers.

The exposure profiles in this analysis are uniquely constructed from fundamental components—emission concentrations and the location, time budget, and activities of household members. As a result we were able...
to determine the contribution of each factor to exposure. In this manner our study is similar to the thorough work of Saksena et al. (19), which used a microenvironment-based analysis in the Indian Himalayas. Moreover, with continuous data on instantaneous pollution levels, we were able to go beyond the single measure of average daily pollution and develop exposure profiles using other descriptive statistics of emission data that better characterize human exposure and therefore extend the current literature on exposure assessment.

**Research Location**

The study took place at Mpala Ranch/Research Centre in Laikipia District, central Kenya (0°20´ N, 36°50´ E). Mpala Ranch, located on semiarid land, is approximately 2,000 m above sea level. The average monthly temperature varies between 17 and 23°C.

Cattle herding and domestic labor are the primary occupations of most of the inhabitants of the 80-100 households on the ranch; members of the remaining households are employed as maintenance staff. The residents have similar tribal backgrounds (Turkana and Samburu), economic status, and diet. The houses in both cattle-herding and maintenance villages are cylindrical with conic straw roofs. Table 1 provides details of housing characteristics in the two villages.

The stoves used by almost all of the households in the study group burn firewood or charcoal as fuel (three households use kerosene). The most common source of fuelwood in the area is species from the Acacia genera. The stove-fuel combinations in the study group are presented in Table 2. Field research at Mpala Ranch began in 1996. During the first 6-8 months of field research we collected background data, including detailed demographic data for all of the households residing on the ranch, and surveys of energy use, energy technology, and related characteristics.

**Methods and Data**

We used the personal DataRAM (PDR) monitor (MIE Inc., Bedford, MA) to measure particulate matter. The PDR monitor uses nephelometric (photometric) monitoring technology with passive sampling, which minimizes interference with normal activities of the household. The maximum response particle size is 0.1-10 µm. Because of this response range, only a fraction of the measured concentration is due to particles ≤ 2.5 µm, which are believed to have the most important health impacts. Studies of particle pollution in both industrialized and developing countries have demonstrated correlations between concentrations of particulate matter ≤ 10 and ≤ 2.5 µm in aerodynamic diameter (PM$_{10}$ and PM$_{2.5}$, respectively) (21,22), but further research on this relationship in the case of biomass smoke is needed. We measured carbon monoxide concentration using the Enerac Pocket 100 monitor (Energy Efficiency Systems, Inc., Westbury, NY). The instruments were sent to the factory approximately once a year for recalibration of measurement range (span), and replacement of PDR measurement chamber and Enerac Pocket 100 sensors. The instruments were zeroed in clean air outside the village compound every day and the PDR measurement chamber was cleaned using pressured air after every 2 days of measurement. Ezzati et al. (15) discussed the relationship between the concentrations of PM$_{10}$ and CO concentrations.

**Data on Temporal Variation of Suspended Particulate Emission and Time-Activity Budgets**

The concentration of PM$_{10}$ was recorded at a distance of approximately 0.5 m from the center of the stove. We placed the monitor on a flat surface at a height of 0.5 m. Because cooking some of the common foods in the area and the lighting and tending of fire are done with the user’s head near the stove, we chose sampling distance as close to the user’s breathing area as was possible under such circumstances. Other criteria for choosing the sampling point were avoiding interference with household activities, ensuring that the instruments could be placed in a stable position and not be damaged because of heat, and ensuring ready standardization of measurement point. PM$_{10}$ concentration was averaged over and recorded in 1-min intervals between the hours of 0630 and 2030 and also during the night when we could ensure that the equipment could be left in the house safely and without disturbance to the household members. In every day of sampling, we also recorded the status of fire (whether it was off, starting, burning, or smoldering), the type of food prepared, and other energy or cooking-related behavior such as adding or moving fuel or the cooking pot, stirring food, etc., during the whole day. The fire status was recorded once every 5-10 min depending on how stable the fire was. Finally, we recorded the location and activities of all of the household members who were present at home during the day. Location data were recorded as whether the person was inside or outside, and whether he or she was near fire (defined as within approximately 1 m of the stove) or far from the fire. Activities and location were recorded as they occurred throughout the day.

Data collection was performed by two field research assistants (one female and one male). The assistants were accompanied by a principal researcher for the first 6 months of data gathering. The data-recording protocol was regularly examined after the first 6 months. Each person was assigned well-defined tasks, especially in the first few minutes of each day when the pollution monitoring equipment was placed in the house. Information such as names and ages of household members was collected independently in the first few months of field research so that on the monitoring days, data sheets for activities for each individual could be prepared before arrival in the house. Test sessions were conducted and the protocols were adjusted to ensure minimum interference with household activities. PM$_{10}$ concentration data, which were logged automatically by the PDR, were downloaded into a personal computer after every day of monitoring. The dates and memory locations of PDR were checked against the other data sheets.

We conducted 210 days of sampling in 55 randomly selected houses in both cattle-herding and maintenance villages. The visits were made on random days of the week. We visited approximately 20% of the households,

![Table 1. Housing characteristics in the cattle-herding and maintenance villages in the study area.](image)

| Village | Characteristic | Cattle-herding | Maintenance |
|---------|----------------|---------------|-------------|
| Diameter | 3–3.5 m | 4–5 m |
| Wall material | Mud, dung, and wood | Stones and mud |
| Wall height | 1.5 m | 2 m |
| Roof material | Wood and grass | Wood and grass |
| Roof height | 1.5 m | 2 m |
| Internal divisions | Yes (mud, dung, and wood) | Yes (plastic) |
| Windows | No | Yes |

![Table 2. Stove-fuel combinations in the study group.](image)

| Stove name | Body | Liner | Fuel | Price (U.S. $) equivalent | Number in use* |
|------------|------|-------|------|--------------------------|--------------|
| Three-stone | NA | NA | Firewood | $0 | 50 |
| Kuni M bili | Metal | Ceramic | Firewood | $4–6 | 26 |
| Upesi | Metal | Ceramic | Firewood | $4–6 | 5 |
| Lira | Metal | Ceramic | Firewood | $4–6 | 1 |
| M etal j i ko | Metal | NA | Charcoal | $4–6 | 24 |
| Loketto | Metal | Metal | Charcoal | $4–6 | 4 |

NA, not applicable.

*Number in use refers to the number of each stove type owned by the households in the sample of 55 households.
randomly selected in both village types, between 6 and 15 times to monitor the intra-household variation in emission concentrations as well as variations in time–activity budgets. We visited another 25% of households once, and the remainder between 2 and 5 times. Included in these days were four nights of activity monitoring of cattle guards and the emissions from the fire that they use for warmth. The demographic characteristics of the individuals in the study households are given in Table 3.

We also conducted extensive interviews with household members and local extension workers on energy technology, cooking practices, and time–activity budgets. In each household, an adult member responsible for cooking was asked in detail about the stove and fuel used by the household, location and times of cooking, and the types of meals prepared. An adult member was also asked about the location and activities of each household member during five time periods in the day (morning, midday, early afternoon, late afternoon, evening, and night), with additional questions about location and activities during cooking. Extension workers were asked the same questions separately.

Data on spatial variation of indoor air pollution. We also collected data on the spatial distribution of indoor air pollution. These measurements were all conducted in two houses (one in each size group) while the residents were away. We ensured that the fire remained stable for a 15-min period, during which we measured PM$_{10}$ concentration sequentially at 10 points inside the house. Eight of the points were at distances of 0.4, 0.8, 1.2, and 1.9 m from the center of the stove at heights of 0.5 and 1.0 m. Points 9 and 10 were directly above the fire at a height of 1.0 m and in the sleeping area, respectively. These points cover those parts of the house where household activities take place; because of the low roof heights, adults do not commonly stand in the house. Sampling took place once every second for 1 min at each point. We repeated this experiment under different conditions with doors and windows open and closed and with and without a cooking pot on the stove. Seventy-eight repetitions of this experiment were conducted in the two houses. Any measurement during which the status of fire changed (such as transition to smoldering phase) was discarded, which resulted in 68 sets of measurements that were used in analysis.

Data Analysis, Results, and Discussion

In our day-long home monitoring sessions, we collected data on pollution level at a single point [at a distance (x) of 0.4–0.5 m from the center of the stove and a height (z) of 0.5 m]. First, the data on spatial distribution of pollution were used to predict PM$_{10}$ concentration at other points inside the house, which in turn could be combined with data on the location of household members to provide a complete spatial and temporal profile of exposure concentration.

Individual exposure: the role of spatial distribution of pollution. Figure 1 plots the concentration of particulate matter against horizontal distance from the stove (x) for measurements at heights (z) of 0.5 and 1.0 m for various measurement conditions corresponding to door or window being open and/or closed or a cooking pot present and/or absent.

Figure 1 shows that PM$_{10}$ concentration initially drops rapidly with increasing distance from the stove, a pattern that can also be observed for visible smoke in actual conditions of use in Figure 2. Concentration then increases at a low rate after a distance of approximately 0.5 m. Further, points at a height of 1.0 m have slightly higher concentration than those at 0.5 m. This pattern indicates that individual exposure to smoke is dependent on the location of the individual relative to the fire, even in houses as small as those described here.

There are few models for characterizing the indoor dispersion of particulate matter.

Table 3. Demographic characteristics of the study group.

| Age group | Individuals in group (n) | Fraction female | Age (mean ± SD) |
|-----------|--------------------------|-----------------|-----------------|
| 0-5 years | 93                       | 0.56            | 3.0 ± 1.4       |
| 6-15 years| 109                      | 0.56            | 9.7 ± 2.7       |
| 16-50 years| 120                     | 0.54            | 28.4 ± 11.8     |
| >50 years | 23                       | 0.65            | 63.8 ± 9.4      |
| Total     | 345                      | 0.56            | 18.3 ± 17.6     |

The age divisions were chosen because children ≤ 5 years of age have additional susceptibility to acute respiratory infections and at higher ages chronic conditions begin to show. For those between 6 and 50 years of age, we made a division at 15 years of age, the age at which it is common for people to enter the workforce or get married.
Above data, emission concentrations in burning and smoldering periods of the day have average coefficients of variation of 3.2 and 4.0, respectively, indicating large daily variability around the mean (a low background level of combustion takes place throughout the whole day. For the purpose of this analysis we defined burning as the periods when the stove is used for cooking and/or it is in flame. Smoldering refers to periods that the stove is neither in active use nor in flame) (15). Our quantitative and qualitative data on time-activity budgets also indicate that some household members are consistently closest to the fire when pollution level is the highest. These episodes typically occur when fuel is added or moved, the stove is lit, the cooking pot is placed on or removed from the fire, or food is stirred (Figures 2 and 4). One of the most common foods in East Africa, particularly in rural areas, is ugali. Ugali is a porridge made from maize or sorghum flour thickened into a cake. After adding flour to boiling water, the cook continuously stirs the mixture. As water evaporates and the mixture hardens, stirring becomes increasingly vigorous and finally turns into folding the hardened dough.

Throughout the process heat is controlled by increasing the burning rate or decreasing it into a smoldering (and hence very smoky) phase as stirring continues. After the water comes to boil and flour is added, the process takes 15–40 min, during which the cook is very close to the fire, actively controlling the heat or mixing of the flour and stirring.

Other individuals may be systematically outside or away from the house during some of these episodes, especially during the hours when the fire is lit or extinguished. This observation indicates that average daily concentration alone is not a sufficient measure of exposure. Therefore, in addition to mean concentration (m), we used two descriptive statistics for the burning and smoldering phases:

- M mean above the 75th percentile (m_75): we used this statistic for the household members who are closest to the stove during high-pollution episodes caused by cooking activities.
- M mean below the 95th percentile (m_95): we used this statistic to eliminate the effect of large instantaneous peaks that occur, especially when lighting or extinguishing the fire or when fuel is added.

**Individual exposure: day-to-day variability.** In addition to daily variations, we can expect day-to-day variability in exposure to indoor smoke as a result of variation in both emissions and time-activity budget. Emissions in a single household can vary from day to day because of fuel characteristics such as moisture content or density, air flow, type of food cooked, or whether the household uses multiple stoves or fuels. In the above data, for example, the fraction of variance of average burning-period emission concentrations (m) explained by interhousehold variation is 6.5 times the fraction explained by day-to-day variability (R^2 = 0.79). (The ratio, obtained by sequential analysis of variance, is for the fraction of variances explained by each variable alone.) The corresponding ratio for m_95 equals 9.0 (m_95 is less sensitive to instantaneous peaks; R^2 = 0.77). This comparison illustrates that, although considerably smaller than interhousehold variation, emissions in individual households vary from day to day.

We found no indication of systematic seasonal variation in emissions in our study area, which we attribute to the fact that drying wood before use is a common practice among the households in the study group (in all of measurements the firewood used was dry). Activity patterns can also vary because of the seasonal nature of work and school, illness, market days, and so on. Therefore, in addition to use of multiple descriptive statistics for characterizing daily exposure, we constructed measures of exposure that are not solely based on measurements from a single day.

Specifically, rather than using measurements of emission concentration directly, we assigned households to pollution concentration categories. We performed this categorization for the three descriptive statistics (m, m_95, and m_75) for both the burning and smoking periods of the day. Emissions in a single household can vary from day to day because of fuel characteristics such as moisture content or density, air flow, type of food cooked, or whether the household uses multiple stoves or fuels. In the above data, for example, the fraction of variance of average burning-period emission concentrations (m) explained by interhousehold variation is 6.5 times the fraction explained by day-to-day variability (R^2 = 0.79). (The ratio, obtained by sequential analysis of variance, is for the fraction of variances explained by each variable alone.) The corresponding ratio for m_95 equals 9.0 (m_95 is less sensitive to instantaneous peaks; R^2 = 0.77). This comparison illustrates that, although considerably smaller than interhousehold variation, emissions in individual households vary from day to day.

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smoldering phases. We grouped time and activity budgets in a similar manner (including time spent inside the fire and inside during cooking and whether the person cooks regularly/sometimes/never and whether the person performs noncooking household tasks regularly/sometimes/never) using the data from the 210 days of direct observation as well as the supplemental interviews.

The width of the concentration and time categories (i.e., bin size) were smaller in lower ranges to account for larger variability at higher values. Adjacent concentration and time categories were also overlapping to account for gradual transitions. For example, concentration categories for mean PM\(_{10}\) (m) during the burning period were <200; 200–1,000; 500–2,000; 1,000–3,000; 2,000–5,000; 3,000–7,000; and 4,000–10,000 µg/m\(^3\). The concentration categories for m > 75 were <150; 150–300; 300–500; 500–1,000; 1,000–2,000; 2,000–4,000; 4,000–8,000; and 8,000–10,000 µg/m\(^3\). The categories for smoldering period were only slightly different. The groups for time inside the house, as a fraction of the day, were <0.2, 0.2–0.35, 0.3–0.45, 0.45–0.65, and >0.6; these groups for time spent near fire were <0.05, 0.05–0.1, 0.1–0.2, 0.2–0.4, and >0.4.

Households that use multiple stoves or fuels span multiple categories. Further, those households that sometimes cook outside were assigned to two distinct categories, one for each cooking location. The time budget of individuals in the latter group of households is also divided between the two locations accordingly. Table 4 provides a summary of the time spent inside the house and near the fire in demographic groups divided by sex and age, which is similar to the findings of Saksena et al. (19) on male and female time budgets.

**Exposure profiles as the basis of analysis.** We constructed profiles of exposure for each individual in the monitored households based on the combination of time–activity budgets, spatial dispersion, and daily and day-to-day exposure variability. We divided the time budget of household members into the following activities: cooking, noncooking household tasks, warming around the stove, playing, resting and eating, and sleeping. We also considered the set of potential locations where each activity takes place. For example, playing or resting may take place inside the house or outside, cooking activities directly above the fire or slightly farther away, and so on. The activity groups and their related parameters are described in Table 5. We then obtained daily exposure using the following relationship:

$$E = \sum_{i=1}^{6} \sum_{t=1}^{14} w_i t_i c_i$$

where c\(_i\) is the emission concentration in the i\(^{th}\) period of the day, t\(_j\) is the time spent in the j\(^{th}\) microenvironment in the i\(^{th}\) period, and w\(_j\) is the conversion (or dilution) factor for the j\(^{th}\) microenvironment, which converts the emission concentration measurements (at point x = 0.5, z = 0.5) to concentration at the i\(^{th}\) microenvironment using the spatial dispersion analysis described above.

Figure 5 illustrates the average exposure concentration (defined as the PM\(_{10}\) concentration that if sustained for the whole day would result in exposure equal to the total daily exposure of the individual) for total daily exposure for various demographic groups. We obtained these values by using Equation 1 and dividing time budgets among the possible location–activity pairs during both burning and smoldering periods (defined in Table 5) based on interviews, direct observation, and demographic characteristics of the household. In Figure 6 we decompose these values into exposure during high-intensity (i.e., when pollution is described by m > 75) and low-intensity episodes, respectively. Finally, in Figure 7 we compare these values with the average exposure concentration values obtained using only average emissions at a single point and time spent inside (i.e., without taking into account either the spatial distribution of pollution or the role of activity patterns on exposure).

The results in Figures 5–7 illustrate several points. First, in the exposure profile approach, the ratio of female to male total exposure is 0.91, 2.5, 4.8, and 1.2 for the four age groups. Therefore, young and adult women not only have the highest absolute exposure to particulate matter from biomass combustion (2,795 and 4,898 µg/m\(^3\) average exposure concentrations, respectively), but
also the largest exposure relative to that of males in the same age group. Second, the ratios of high-intensity exposure to total exposure for the four age groups are 0.0, 0.40, 0.61, and 0.31 for females and 0.0, 0.02, 0.11, and 0.08 for males. The larger value for young and adult women illustrates that high-intensity episodes account for a considerably larger fraction of exposure of those household members who are closest to fire at such times (and also much larger in absolute values because female exposure has larger base values). In terms of the relative contributions of cooking and living microenvironments, these results are consistent with those of Saksena et al. (19), who used direct monitoring of concentration in different microenvironments in the Indian Himalayas rather than a spatial model. The differences between the two studies include different housing characteristics, potentially different activity patterns for some demographic subgroups, and the use of average concentration versus multiple descriptive statistics for characterizing pollution. The combined effect of these factors seems not to influence the overall exposure distributions. However, each is important and should be considered in any study of exposure to indoor smoke. Third, the ratios of exposure estimates using average emissions at a single point (i.e., Figure 7) to those using the exposure profile approach (i.e., Figure 5) for the four age groups are 0.97, 0.44, 0.29, and 0.51 for females and 0.97, 0.91, 0.83, and 0.79 for males. The large variation of this ratio among the demographic groups indicates that ignoring the spatial distribution of pollution and the role of activity patterns on exposure could not only result in inaccurate estimates of exposure but also—and possibly more importantly—could bias the relative exposure levels for different demographic groups. The exposure of women who cook, and who therefore are most affected by high-intensity pollution episodes, would be underestimated most severely by using average pollution alone. This would in turn result in systematic bias in assessment of the health impacts of exposure and benefits from any intervention strategy.

**Conclusions**

We used continuous PM_{10} monitoring, data on spatial dispersion of indoor smoke, and detailed quantitative and qualitative data on time-activity budget to construct measures of exposure to indoor particulate matter that take into consideration individual patterns of exposure, including daily and day-to-day variability. The inclusion of these factors beyond the commonly used single measure of average pollution level illustrates that average pollution concentration alone is not a sufficient measure of human exposure in situations where a large fraction of exposure occurs during high-intensity emission episodes, such as the case for individuals responsible for cooking using biomass stoves. Therefore, in designing intervention schemes such as new stove technology, worst-case scenarios—such as emissions during lighting, extinguishing, or moving of fuel—should receive as much attention as average emission levels (15). Further, our results indicate the importance of detailed exposure assessment in quantifying the exposure-response relationship for indoor particulate matter that exhibits such episodic characteristics. Finally, the role of high-intensity exposure raises a research question about inhalation and pulmonary deposition of particulate matter under different exposure circumstances. Important recent work has shed new light on the dispersion of aerosol bolus in human airways (26). New research that integrates modeling, laboratory testing, and field trials is needed to consider dispersion, deposition, and health impacts as a function of pollution intensity.

**REFERENCES AND NOTES**

1. World Bank. World Development Report: Investing in Health. New York: Oxford University Press, 1993.
2. Smith KR. The national burden of disease from indoor air pollution in India. Presented at Indoor Air 99: The 8th International Conference on Indoor Air Quality and Climate, Edinburgh, Scotland, 8-13 August 1999:13-18.
3. WHO. World Health Report 1999. Geneva: World Health Organization, 1999.
4. WHO. World Health Report 1998. Geneva: World Health Organization, 1998.
5. Chen BH, Hong CJ, Pandey MR, Smith KR. Indoor air pollution in developing countries. World Health Stat Q 43:127-138 (1990).
6. Armstrong RM, Campbell HI. Indoor air pollution exposure and respiratory infections in young Gambian children. Int J Epidemiol 20:424-429 (1991).
7. Ellyard A. Cooking fuel smoke and respiratory symptoms among women in low-income areas in Maputo. Environ Health Perspect 104:980-989 (1996).
8. Ellyard A, Gunkel D, Aguilera S. A comparison of cooking stoves in Indonesia. Int J Epidemiol 20:198-202 (1991).
9. Ellyard A, Gunkel D, Aguilera S. A comparison of cooking stoves in Indonesia. Int J Epidemiol 20:198-202 (1991).
10. World Health Organization. Health and the Urban Environment. Geneva: World Health Organization, 1998.
11. World Health Organization. Health and the Urban Environment. Geneva: World Health Organization, 1998.
12. World Health Organization. Health and the Urban Environment. Geneva: World Health Organization, 1998.
13. World Health Organization. Health and the Urban Environment. Geneva: World Health Organization, 1998.
14. World Health Organization. Health and the Urban Environment. Geneva: World Health Organization, 1998.
15. World Health Organization. Health and the Urban Environment. Geneva: World Health Organization, 1998.
16. World Health Organization. Health and the Urban Environment. Geneva: World Health Organization, 1998.
17. World Health Organization. Health and the Urban Environment. Geneva: World Health Organization, 1998.
18. World Health Organization. Health and the Urban Environment. Geneva: World Health Organization, 1998.
19. World Health Organization. Health and the Urban Environment. Geneva: World Health Organization, 1998.
9. Ezzati M, Kammen DM, Singer BH. The health impacts of exposure to indoor air pollution from biofuel stoves in rural Kenya. Presented at Indoor Air 99: The 8th International Conference on Indoor Air Quality and Climate, Edinburgh, Scotland, 8–13 August 1999:130–135.
10. Pandey MR. Domestic smoke pollution and chronic bronchitis in a rural community of the hill region of Nepal. Thorax 39:337–339 (1984).
11. Pandey MR, Neupane RP, Gautam A, Shrestha IB. Domestic smoke pollution and acute respiratory infections in a rural community of the hill region of Nepal. Environ Int 15:337–340 (1988).
12. Smith KR, Samet J M, Romieu I, Bruce N. Indoor air pollution in developing countries and acute lower respiratory infections in children. Thorax 55:518–532 (2000).
13. Smith KR. Indoor air pollution in developing countries: growing evidence of its role in the global burden of disease. Presented at Indoor Air 96: The 7th International Conference on Indoor Air Quality and Climate, Nagoya, Japan, 21–26 July 1996.
14. WHO. WHO Air Quality Guidelines. Geneva: World Health Organization, 1999.
15. Ezzati M, Mbinda BM, Kammen DM. Comparison of emissions and residential exposure from traditional and improved biofuel stoves in rural Kenya. Environ Sci Technol 34:578–583 (2000).
16. Bruce N, Neufeld L, Boy E, West C. Indoor biofuel air pollution and respiratory health: the role of confounding factors among women in highland Guatemala. Int J Epidemiol 27:454–458 (1998).
17. Ballard-Tremeer G, Jawurek HH. Comparison of five rural, wood-burning cooking devices: efficiencies and emissions. Biomass Bioenergy 11:419–430 (1996).
18. Boleij J SM, Ruigewaard P, Hoek F, Thairu H, Wafula EM, Onyango FE, De Koning H. Domestic air pollution from biomass burning in Kenya. Atmos Environ 23:1677–1681 (1989).
19. Saksena S, Prasad R, Pal RC, Joshi V. Patterns of daily exposure to TSP and CO in the Garhwal Himalaya. Atmos Environ 26A:2125–2134 (1992).
20. Reid HF, Smith KR, Sherchand B. Indoor smoke exposures from traditional and improved cookstoves: comparisons among rural Nepalese women. M T Res Dev 6:293–304 (1986).
21. Naeher LP, Leaderer BP, Smith KR, Grajeda R, Neufeld L, Mage D, Boleij J SM. CO as a tracer for assessing exposure to particulates in wood and gas cookstove households of Highland Guatemala. Presented at Indoor Air 96: The 7th International Conference on Indoor Air Quality and Climate, Nagoya, Japan, 21–26 July 1996:417–422.
22. Wilson R, Spengler JD, eds. Particles in Our Air: Concentrations and Health Effects. Cambridge, MA: Harvard University Press, 1996.
23. Smith KR. Biofuels, Air Pollution, and Health: A Global Review. New York: Plenum Press, 1987.
24. Dresher AC, Lobascio C, Gadgil AJ, Nazaroff WW. Mixing of a point source pollutant by forced convection. Indoor Air 5:204–214 (1995).
25. Baughman AV, Gadgil AJ, Nazaroff WW. Mixing of a point source pollutant by natural convection flow within a room. Indoor Air 4:114–122 (1994).
26. Sarangapani R, Wexler AS. Modeling aerosol bolus dispersion in human airways. J Aerosol Sci 30:1345–1362 (1999).