Environ. Sci. Technol. **2000**, *34,* 578−583

Comparison of Emissions and Residential Exposure from Traditional and Improved Cookstoves in Kenya

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Suspended particulate matter and carbon emissions from the combustion of biomass, in addition to their environmental consequences, have been causally associated with the incidence of respiratory and eye infections. Improved stoves offer the potential for emissions reduction. We compare the emissions of suspended particulate matter and carbon monoxide from traditional and improved biofuel stoves in Kenya under the actual conditions of household use. Data for analysis is from 137 14-h days of continuous real-time emission concentration monitoring in a total of 38 households. Our analysis shows that improved (ceramic) wood-burning stoves reduce daily average suspended particulate matter concentration by 48% (1822 μg/m^3; 95% C.I. 663−2982) during the active burning period and by 77% (1034 μg/m^3; 95% C.I. 466−1346) during the smouldering phase. Ceramic stoves also reduce the median and the 75th and 95th percentiles of daily emission concentration during the burning period and the 95th percentile during the smouldering phase, and therefore shift the overall emission profile downward. Improved charcoal-burning stoves also offer reductions in indoor air pollution compared to the traditional metal stove, but these are not statistically significant. The greatest reduction in emission concentration is achieved as a result of transition from wood to charcoal where mean emission concentrations drop by 87% (3035 μg/m^3; 95% C.I. 2356−3500) during the burning period and by 92% (1121 μg/m^3; 95% C.I. 626−1216) when smouldering as well as large reductions in the median and 75th and 95th percentiles. These results indicate that transition to charcoal, followed by the use of improved wood stoves, are viable options for reduction of human exposure to indoor air pollution in many developing nations.

Introduction

Approximately one-half of the world's population relies on biomass—wood, crop residues, dung, and charcoal—as the primary source of domestic energy, burning 2 billion kg of biomass every day in developing countries (*1, 2*). Biomass accounts for more than one-half of national energy and as much as 95% of domestic energy in some developing countries (*2, 3*).

Exposure to indoor air pollution, especially to suspended particulate matter, resulting from the combustion of biomass has been implicated as a causal agent of acute respiratory infections (ARI) and eye infection (*4*−*6*). Acute and chronic respiratory infections together account for over 10% of the total burden of disease in developing countries (*7, 8*). In 1997 and 1998, the leading cause of death from infectious diseases was acute lower respiratory infections with an estimated 3.7 and 3.5 million deaths worldwide for the 2 years, respectively (*8, 9*).

"Improved" (high-efficiency and low-emission) cookstoves offer the potential to reduce exposure to indoor air pollution (*10, 11*). Improved stoves were initially of interest to the international development community because of their potential to reduce fuel consumption and thus deforestation (*12, 13*). The public health benefits from reduction in exposure to indoor smoke as well as the reduction in carbon emissions became the subject of attention soon after. This "double-dividend" —improvements in public health while reducing adverse environmental impacts—focused a great deal of effort on the design and dissemination of improved stoves (*1, 14, 15*).

Initial works on the benefits of improved stoves were often marked by a lack of detailed data on stove performance. Efficiencies and emissions, for example, were often measured in controlled environments with the stoves only used by technical experts under conditions dissimilar to those in the field (*13, 16*). More recently, the attention of research community has shifted from such ideal operating conditions to monitoring stove performance under actual conditions of use, taking into account the various social and physical factors that would limit the use of these stoves all together or result in "suboptimal" use (*17, 18*). As a result of these studies the initially perceived high level of benefits from improved stoves has been called into question (*19, 20*).

In this paper, we analyze, under the conditions of actual use, the performance of an array of stove-fuel combinations used extensively by Kenyan households. They include the traditional open fire as well as a set of improved cookstoves. We conducted continuous real-time monitoring of the level of indoor air pollution (suspended particulate matter and carbon monoxide) in 38 houses for a total of 137 days, for approximately 14 h per day. In this manner, our work complements the thorough work of Ballard-Tremeer and Jawurek (*19*) who compare the performance of five rural wood-burning stoves using standard tests.

Our analysis is motivated by the need to understand the health impacts of household energy technologies (fuel and stove combinations). Elsewhere we have demonstrated that (1) pollution levels vary a great deal throughout the day; (2) household members are closest to fire when pollution level is the highest; and (3) in addition to average exposure, the "intensity" of exposure is likely to be a determinant of respiratory and eye infections (*6, 21*). Based on these results, we note that average pollution level alone, especially if measured over short time intervals, does not sufficiently explain the health impacts of household energy technology. We therefore go beyond this individual measure in comparing the various cookstoves and develop a framework to use other descriptive statistics, which may be better indicators of human exposure.

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10.1021/es9905795 CCC: $19.00
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Published on Web 01/15/2000

TABLE 1: Stove-Fuel Combinations in the Study Group

stove name	material: body	material: liner	fuel	price (U.S. $ equiv)
three-stone	N/A	N/A	firewood	0
Kuni Mbili	metal	ceramic	firewood	6
Upesi	metal	ceramic	firewood	6
Lira	metal	ceramic	firewood	6
Metal Jiko	metal	N/A	charcoal	1.5
Kenya Ceramic Jiko (KCJ)	metal	ceramic	charcoal	5
Loketto	metal	metal	charcoal	6

Finally, we explore the correlation between suspended particulate and carbon monoxide concentrations, since it has been hypothesized that carbon monoxide could provide an inexpensive tracer for particulate matter (*10*).

Research Location

The study takes place at Mpala Ranch/Research Centre, in Laikipia District, central Kenya (0°20′N, 36°50′E). Cattle herding and domestic labor are the primary occupations of the residents of the ranch, who have similar tribal backgrounds (Turkana and Samburu) and diet. Kenya has a long history of improved stove programs with an estimated 1 million stoves disseminated mostly in urban areas, and a well-established commercial stove manufacturing sector (*22, 23*). The stoves used by the households in the study group use firewood or charcoal (and kerosene in the case of one household) as their fuel. All households were trained on the proper use of improved stoves by local extension workers. The stove-fuel combinations are presented in Table 1 and illustrated in the panels of Figure SI-1. The improved stoves (with the exception of *Loketto*) consist of a ceramic liner and a metal body.

Methods and Data

Measurement of suspended particulate matter was carried out using the *personal*DataRAM manufactured by MIE, Inc. (Bedford, MA) (particle size of maximum response: 0.1−10 μm). Carbon monoxide was measured using an Enerac Pocket 100 manufactured by Energy Efficiency Systems, Inc. (Westbury, NY). The equipment were calibrated in clean air outside the village compound every day, and the measurement chamber of *personal*DataRAM was cleaned using pressured-air after every 2 days of measurement.

Data were recorded at a distance of approximately 0.5 m from the stove, at a height of approximately 0.5 m. The concentration of suspended particulate matter was averaged over and recorded in 1-min intervals between the hours of 7:00 and 20:00. During the same period, the carbon monoxide concentration was measured in 5- or 10-min intervals (depending on how stable the fire was) averaged over a period of 10−20 s. Throughout this period, we also recorded the status of the fire (whether it was off, starting, burning, or smouldering), the type of food prepared, and other energy or cooking related behavior such as the addition or moving of fuel. Finally, we recorded the location and activities of those household members who were present at home during the day.

Data used in this paper were collected between 1997 and 1999 as a part of a larger ongoing study of the relationship between energy technology, indoor air pollution, and public health. Data collection took place for 1 day in some of the households. Others were visited multiple times. Data from the latter group of households was used to monitor the intrahousehold variation in emission concentration, such as seasonal variations. We found no indication of systematic seasonal variation, 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). A total of 137 days of sampling was conducted in 38 randomly selected houses (with similar housing characteristics) in both cattle-herding villages (or *bomas*) and larger villages that house the maintenance staff. Figures1 and 2 illustrate a sample of data for a single house for a single day.

Results and Discussion

Comparison of Average Emission Concentrations. Figures SI-2 and SI-3 illustrate the average suspended particulate concentration and carbon monoxide concentration, respectively, averaged over the *burning* period (panel a) and the *smouldering* period (panel b), respectively, for various stove-fuel combinations. (In most houses a low background level of combustion took place throughout the whole day. For the purpose of this analysis we defined *burning* as the periods when the stove was used for cooking and/or it was in flame. *Smouldering*, therefore, refers to periods that the stove was neither in active use nor in flame.) Quantitative comparison of these values using the two-sided two-sample t-test are given in Tables SI-1−SI-4 for suspended particulate matter (we assumed unequal variances in the t-tests, to account for possible differences in stove attributes). None of the changes in carbon monoxide emission concentrations was statistically significant.

These comparisons indicate the following results:

(1) Improved wood-burning cookstoves reduce average daily suspended particulate matter emission concentration during burning time by 48% (1822 μg/m^3; 95% C.I. 663−2982).

(2) Average emissions concentration during the smouldering period declines by 77% (1034 μg/m^3; 95% C.I. 466−1346). We attribute the larger relative reduction during smouldering compared to burning to the operation of the stove, not to thermodynamics of combustion. Three-stone stove is often used with larger pieces of wood that remain in the stove for a longer period after cooking has taken place. Improved stoves, on the other hand, are used with smaller pieces of wood which stop burning shortly after the active use of the stove is terminated. Moreover, since ceramic stoves are portable, it is not uncommon for people to remove them from the house once cooking has taken place (see also the section on the comparison of other descriptive statistics below).

(3) For charcoal stoves, during the burning period the average suspended particulate emission concentrations of *KCJ* and *Loketto* are 65% (578 μg/m^3; 95% C.I. −280−894) and 63% (559 μg/m^3; 95% C.I. −290−894) lower than that of *Metal Jiko*, respectively. This reduction is statistically only weakly significant (potentially due to the small sample size). Although the absolute value of these reductions are small (relative to that between improved and traditional wood stoves), the improved charcoal stoves, with emission concentration levels of approximately 300 μg/m^3, are the only biomass stoves in the study group that approach international standards. The U.S. EPA standard for PM_{10}, for example, requires a 24-h average of no more than 150 μg/m^3.

(4) Improved charcoal stoves (*KCJ* and *Loketto*) do not reduce emission concentration significantly during the smouldering period relative to the *Metal Jiko*. Unlike wood-burning stoves, improved charcoal stoves do not change the mode of operation compared to the *Metal Jiko*. All stoves continue to combust slowly at a low background rate, or alternatively all can be removed from the house, and hence the small reduction while smouldering.

(5) All stove categories, and in particular the three-stone fire, exhibit large variability of emission concentrations. The *interquartile ratios* (defined as the difference between the third and first quartiles normalized by the median; a measure

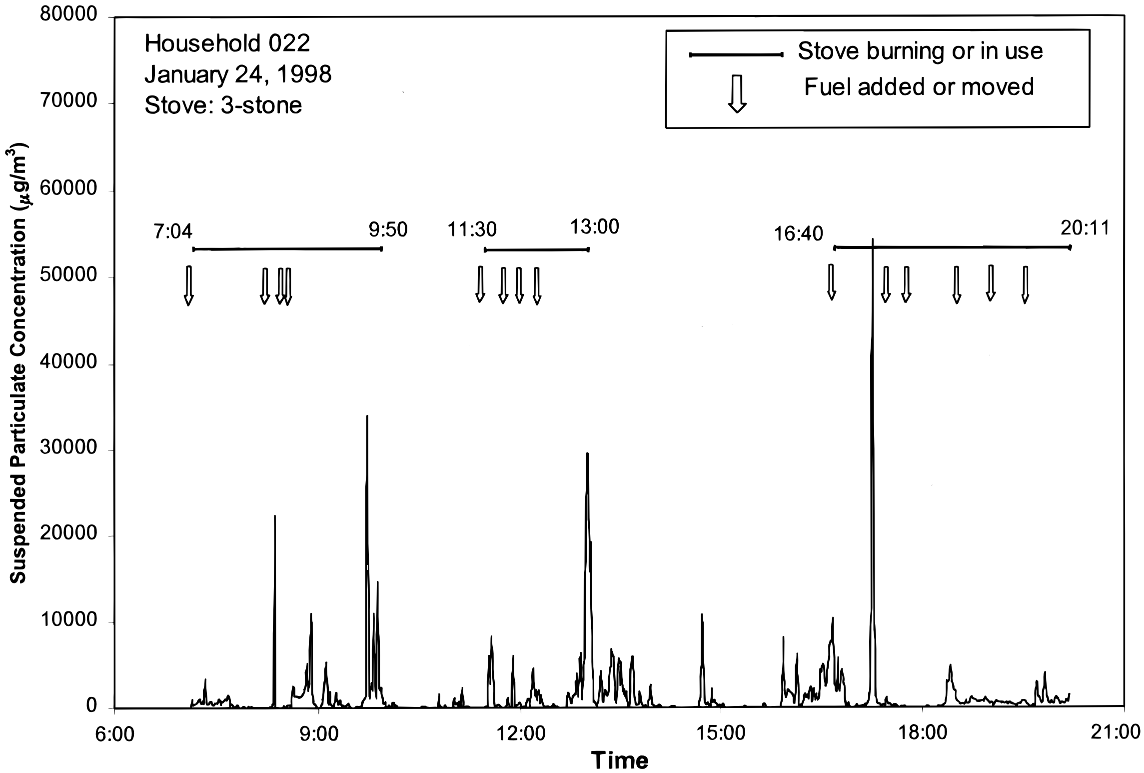

FIGURE 1. Concentration of suspended particulate matter for a single day for a single household. Sampling took place between the hours of 7:04 in the morning and 20:11 in the evening over 1-min intervals. The figure also illustrates the status of the fire during the day and the addition of fuel.

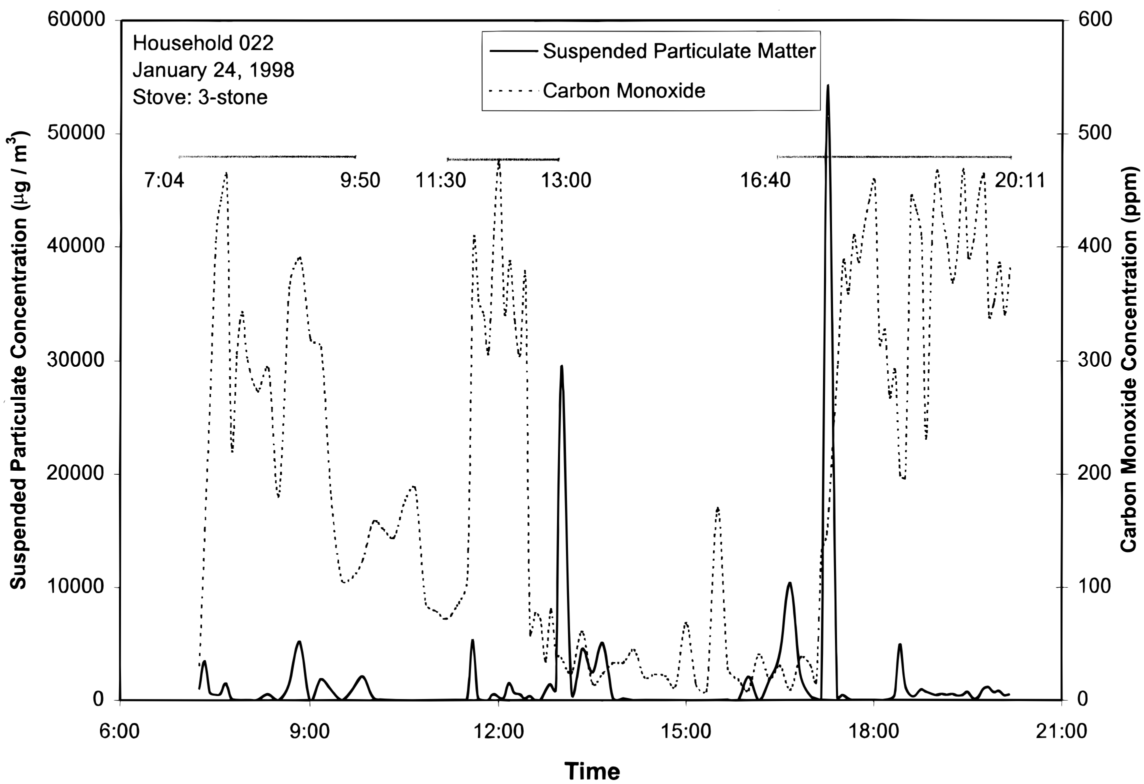

FIGURE 2. Concentration of suspended particulate matter and carbon monoxide for a single day for a single household. Sampling took place between the hours of 7:04 in the morning and 20:11 in the evening over 5- or 10-min intervals.

of the spread of data) for the mean emission concentrations of three-stone, improved wood stoves, *Metal Jiko*, *KCJ*, and *Loketto* during the burning period are 1.96, 1.09, 1.02, 1.80, and 1.07, respectively, illustrating the large range of emissions within individual stove categories. This variability illustrates that how a stove is used may be as important of a determinant of emission as the stove type. This confirms under actual conditions of use the laboratory finding of Ballard-Tremeer and Jawurek (*19*) on the overlap between range of emissions from open fire and ceramic stoves.

(6) The largest reduction in suspended particulate emission concentration is achieved with transition from wood to charcoal in both burning and smouldering states. In the burning period transition from wood to charcoal reduces the average emission concentration by 87% (3035 $\mu g/m^3$; 95% C.I. 2356−3500) and in the smouldering period by 92% (1121 $\mu g/m^3$; 95% C.I. 626−1216).

During the burning period, even the comparison of the best-case scenario for wood stoves (improved wood stoves) and worst-case scenario for charcoal stoves (*Metal Jiko*) exhibits a drop in suspended particulate emission concentration of 54% (1048 $\mu g/m^3$; 95% C.I. −114−1942) when charcoal is used. During the smouldering period, the best-case scenario for wood stoves (improved wood stoves) has comparable emission concentration to the worst-case scenario for charcoal stoves (*Metal Jiko*) but is significantly more polluting than the best-case scenario for charcoal stoves (*KCJ* and *Loketto* have 84% (261 $\mu g/m^3$; 95% C.I. 94−312) and 95% (297 $\mu g/m^3$; 95% C.I. 139−312) lower emission concentrations than improved wood stoves). As above, we attribute this relative improvement of improved wood stoves during the idle period to their operation, since they continue to smoulder for a shorter period than the open fire.

Is Average Emission Concentration a Sufficient Indicator of Exposure? Comparison of Other Descriptive Statistics. Elsewhere (*6, 21*) we have demonstrated that (1) smoke emissions exhibit a very large level of variability throughout the day. In the above data, for instance, the suspended particulate concentration has average *coefficients of variation* (defined as the ratio of standard deviation to mean; a measure of the variability of data relative to its mean) of 3.2 and 4.0 during the burning and the smouldering periods, respectively, indicating large daily variability around the mean (see also Figure 1); (2) a consistent set of household members are closest to fire when pollution level is the highest—when fuel is added or moved, the pot is removed from the fire, or the food is stirred; and (3) in addition to average exposure, the “intensity” of exposure is likely be a determinant of respiratory and eye infections.

These points indicate that average emission concentration alone is not a sufficient measure of the health impacts of energy technology and that other descriptive statistics, ones that consider the above points about human behavior and exposure, are necessary in stove characterization. We use the following descriptive statistics for the reasons stated. (1) Daily median: to account for the large daily variability of emissions and conduct stove comparisons that are not sensitive to large instantaneous peaks. (2) Daily 75th percentile: to account for the role of individual behavior and activity pattern in which some household members are closest to the fire when it has its highest pollution. (3) Daily 95th percentile: to compare stoves not at their “normal” operating mode but at their worst conditions to account for potential impacts of exposure intensity—exposure to extremely high levels of pollution within short periods of time (i.e., episodes on the order of a few minutes).

We limit this analysis to suspended particulate emission not only because of its causal association with respiratory infection but also because it exhibits considerably larger variation among different stove types.

Figures SI-4−SI-6 compare the above three descriptive statistics for suspended particulate concentration for both the burning period (panel a) and the smouldering period (panel b). Quantitative comparison of these values using the two-sided two-sample *t*-test are given in Tables SI-5−SI-10.

Emission reductions due to fuel change (from wood to charcoal) is presented in Tables SI-11 and SI-12 for the burning and smouldering periods, respectively.

The above comparisons indicate the following results:

(1) During the burning period, improved wood stoves provide an overall reduction in the emission concentration compared to three-stone fire. In addition to the mean concentration, the ceramic wood stoves also reduce the the daily median emission concentration by 60% (446 $\mu g/m^3$; 95% C.I. 225−667), the 75th percentile by 52% (1375 $\mu g/m^3$; 95% C.I. 618−2132), and the 95th percentile by 56% (9374 $\mu g/m^3$; 95% C.I. 4204−14543). Therefore, these stoves shift the whole distribution of emission concentration downward, thus reducing human exposure. In particular the reduction in the median and the 75th percentile can be interpreted as lower emissions when people are closest to the stoves. The reduction in the 95th percentile reduces the most intense exposure episodes.

(2) When the stoves are not actively burning, the median emission concentration of improved wood stoves is only 29 $\mu g/m^3$ (35%) lower than the open fire and the difference is not statistically significant; the 244 $\mu g/m^3$ (49%) reduction in the 75th percentile is only weakly significant; but the 95th percentile decreases significantly by 75% (4559 $\mu g/m^3$; 95% C.I. 1391−6039). We saw earlier that ceramic wood stoves also reduce the mean daily emission concentration during the smouldering period compared to three-stone fire. Simultaneous reductions in mean and the 95th percentile, but not in median and the 75th percentile, emphasize the idea that during the smouldering periods of the day most emissions occur in a short (but intense) period; for the rest of the time both stove types combust at low (and similar) levels.

The daily emission concentration profiles illustrate that this short period is often immediately before or immediately after combustion, when stove is being lit or smouldering. Coupled with this reduction during noncooking period is our quantitative and qualitative observation that at least some household members are likely to be in the house for a period after the completion of cooking, to serve/eat/drink food or tea, for example, to clean the dishes used for cooking, or to sweep the house. With exposure extending beyond the active burning period, smouldering period reductions also provide benefits in lowering human exposure.

(3) The improved charcoal stoves (*KCJ* and *Loketto*) offer only moderate emission reductions compared to the older *Metal Jiko*. *KCJ* and *Loketto* reduce median emission concentration during the burning period by 656 $\mu g/m^3$ (85%) and 748 $\mu g/m^3$ (97%), but the results are only weakly statistically significant. These stoves do not offer any reductions during the smouldering period or in the higher end of emission concentration in the burning period (75th and 95th percentiles). In the smouldering period all charcoal stoves are extremely similar since charcoal, a relatively clean fuel, combusts slowly and without large emission fluctuations. The lack of significance in reductions during the burning period can be partially attributed to small sample size. But we also note that given the large similarity between *Metal Jiko* and the improved charcoal stoves (they both burn charcoal in a small compartment) and the physical attributes of charcoal combustion (relatively homogeneous fuel with high carbon content) similar emission levels may be expected.

(4) The largest reduction of emission concentration profiles is achieved through a transition from wood to charcoal. With this fuel transition, during the burning period median emission concentration decreases by 62% (417 $\mu g/m^3$; 95% C.I. 137−675), the 75th percentile by 81% (1972 $\mu g/m^3$; 95% C.I. 1368−2423), and the 95th percentile by 91% (14036 $\mu g/m^3$; 95% C.I. 10755−15403). During smouldering the median does not decline significantly, but the 75th and 95th percentiles decrease by 84% (391 $\mu g/m^3$; 95% C.I. 188−463) and 96% (5223 $\mu g/m^3$; 95% C.I. 2499−5461), respectively. These reductions imply a large overall downward shift in the pollution profile and, therefore, human exposure, as a result

of charcoal use.

(5) Similar to the mean emission concentration, the large variations in daily median within each stove-fuel group illustrates that the benefits of improved stoves could theoretically be achieved through the best-mode operation of the traditional ones.

In the above analysis we have only considered the emission concentrations at a single point, near the fire. Pollution concentration, and hence individual exposure, depends on the distance from the stove in addition to the stove emissions. We have collected detailed data on the time-activity budget of the individuals in the study group and conducted measurements that provide estimates of the spatial distribution of pollution. Estimates of personal exposure based on this data set are provided in ref *21*.

Policy Implications of Findings. The above findings raise two important policy questions: First, although from an environmental point of view charcoal is more damaging than fuelwood (*12*), benefits to public health are likely to be considerable. This tension is a reminder of the need for integrated approaches to technology, environment, and health in designing successful intervention strategies. Second, from a public health policy perspective, our findings on the reduction in exposure pose the question raised by Bruce et al. (*24*) on whether the reductions are sufficiently large so that health benefits can be observed? We discuss this question in detail elsewhere (*21*). Finally, the improved stoves in the study area were found not to offer significant reductions in carbon monoxide emission concentrations. Since these concentrations remain above the recommended WHO concentration of 87 ppm for more than 15 min (*25*), the public health benefits of these stoves is from the reduction in suspended particulate matter only.

Carbon Monoxide as an Indicator of Suspended Particulate Matter. High correlation has been reported between carbon monoxide and suspended particulate concentrations, indicating the possibility of using the former as an inexpensive marker for the more costly to measure suspended particulate matter (*10, 26*). In this section we investigate this potential in detail, once again in the framework of human exposure.

A simple linear model, given by eq 1, may be used for prediction of suspended particulate matter concentration from that of carbon monoxide

$$[PM_{10}] = \alpha_0 + \alpha_1[CO] + \epsilon \qquad (1)$$

where $[PM_{10}]$ and [CO] are the concentrations of particulate matter and carbon monoxide, respectively, and ϵ is the regression residual. Rather than considering the question of "prediction of suspended particulate matter from carbon monoxide" as a purely statistical one, we impose the physical restriction that, in the absence of any combustion, particulate matter and carbon monoxide concentrations should both be zero simultaneously (in practice the concentrations will only be close to zero due to the small background levels). In other words, we force the linear model of eq 1 to pass through the origin ($\alpha_0 = 0$).

We start the analysis of the performance of this model by considering all fuels and stoves together and then decompose the large sample into groups based on fuel and later stove type. The results for these analyses for mean concentrations (provided in Tables SI-13–SI-16) show that when aggregate comparison across all fuels and stoves is made, the R^2 values—a measure of the explanatory of power of carbon monoxide (CO) concentration—are low ($\leq$0.23) (Note that in this case, where [CO] is the only explanatory variable, the R^2 of the regression equals the square of the correlation coefficient between the two variables). When the measurements are separated into their fuel and stove subgroups, the measures of correlation improve in general (R^2 in the range 0.14–0.91) although still lower than those (approximately 0.9) observed by Naeher et al. (*26*) and McCracken and Smith (*10*).

This categorization illustrates another important characteristic of using CO as PM_{10} tracer: the coefficient of the predictive linear relationship (α_1) is highly dependent on the conditions under which emissions are measured—type of fuel and stove in this case. This dependence on the specific conditions reduces the applicability of CO as the indicator of suspended particulate matter, since the estimation of the locally specific parameters requires the very thing that the method attempts to avoid, simultaneous measurement of the two pollutants.

From an exposure assessment perspective, there is another problem with using carbon monoxide as the indicator of suspended particulate matter. The above correlation as well as those observed by Naeher et al. (*26*) and McCracken and Smith (*10*) are among daily average values. For most people, however, significant exposure occurs only during certain parts of the day, in an *episodic* manner (*21*). As Figure 2 illustrates, the *instantaneous* concentrations of the two pollutants show weak correlation. Table SI-17 provides a summary of the day-long temporal correlation between these two pollutants. The lack of correlation ($R \leq 0.26$) quantitatively confirms the suspicion raised in Naeher et al. (*26*) and observed in one of the trials of Ballard-Tremeer and Jawurek (*19*) that the temporal relationship is highly dependent on the burning status of the fire.

Finally, the concentration of suspended particulate matter exhibits sharper fluctuations between a generally low background level and very large peaks than carbon monoxide, as seen in Figure 2. Numerically, the average value of the *coefficient of skewness* (defined as $m_3\sigma^{-3}$ where m_3 is the third moment and σ the standard deviation; a measure of how symmetric or skewed a distribution is with a coefficient of skewness of zero corresponding to a symmetric distribution) for suspended particulate matter concentration is 7.8 versus 1.0 for carbon monoxide concentration. The highly skewed distribution of PM_{10} relative to CO is another indication of the fact that the latter does not provide full information on the extent of variability of the former.

Carbon monoxide monitoring will remain a useful tool in qualitative ranking of households in terms of emission levels. But given the recent commercial availability of small-size monitoring devices for suspended particulate matter and the critical importance of the episodic nature of exposure to indoor smoke, the usefulness of the former as a means for detailed assessment of exposure to suspended particulate matter is limited.

Acknowledgments

This research was supported by grants from Summit and Compton Foundations to D. M. Kammen and from Princeton University's Council on Regional Studies and Centre of International Studies (through a grant from MacArthur Foundation) and Social Science Research Council to M. Ezzati. Support for cookstove dissemination workshops was provided by ASAL Development Program Laikipia District. African Academy of Sciences provided generous institutional support in Kenya. We are grateful to Mark Egelian, Peter Ekuam, Mary Lokeny, and Jackson Ngisirkale for invaluable assistance in data collection and to the residents of Mpala Ranch for their kind hospitality which made data collection possible. This paper has benefited from comments by two anonymous reviewers.

Supporting Information Available

Tables and figures depicting experimental data. This information is available free of charge via the Internet at http://pubs.acs.org

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Received for review May 24, 1999. Revised manuscript received October 6, 1999. Accepted November 18, 1999.

ES9905795